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On the Change of Monthly Sea Surface Temperature in the Western North Pacific (IV)

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(Received March 15, 1973)

Abstract: The variation of monthly mean sea surface temperature in the Western North Pacific is approximated by a simple model. This is nearly the same as a model which was constructed to express the variation of ten-day mean sea surface temperature at Ocean Weather Station T in the previous paper. The variation of sea surface temperature is expressed by a linear combination of sea surface temperature and heat exchange between the sea and the atmosphere, and effects of horizontal advection and diffusion are assumed to be dependent on month and not on year. Though the approximation is not satisfactory, the model may be used to estimate mean sea surface temperature in the following month. Furthermore, rough estimations are tried on the effects of meteorological elements on the variation of sea surface temperature based on the model.

1. Introduction

In the previous paper (MORIYASU, 1971), a model was constructed to approximate the variation of ten-day mean sea surface temperature at the ocean weather station, T, located at 29°N, 135°E. And satisfactory results were obtained for the first approximation. This trial was made as the preliminary step for monthly mean sea surface temperature in the Western North Pacific. Though some problems remain unsolved, the model is applied to the variation of monthly mean sea surface temperature in the Western North Pacific in this report.

Monthly mean sea surface temperature used here is one for a quadrangle of 5 degrees in longitude and 2 degrees in latitude and is compiled by the JAPAN METEOROLOGICAL AGENCY (1966, 1967a, 1967b, 1968 and 1970). Thirty quadrangles taken in this report are located between 30°N and 48°N to the west of 160°E and the period of statistics is 5 years from 1961 to 1965. The value of various elements is mean of values collected in individual quadrangle in each month instead of at a fixed station in each ten-day in the previous report. It is noticed that the model includes neither horizontal advection nor diffusion explicitly. This results from the situation that the variation of sea surface temperature at a point was studied

without information on temperature around the point. Therefore, this model is expected to be improved in the next stage. In this report, it is examined how the variation of monthly mean sea surface temperature is approximated by this model and rough estimations are made on the effects of wind speed and cloudiness on the variation of sea surface temperature.

2. The model

The model used here is the one in the previous report, but a slight modification is made. The description on the model is given again to express the modification. The variation of temperature θ in the surface layer is expressed by

$$\rho c_p \frac{\partial \theta}{\partial t} = -\rho c_p \left(u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} \right) - \rho c_p w \frac{\partial \theta}{\partial z} + \rho c_p K_H \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) + \rho c_p K_V \frac{\partial^2 \theta}{\partial z^2} - \frac{\partial Q'}{\partial z} .$$

The notation is as follows:

ρ density of water
c_p specific heat at constant pressure
u east component of current velocity
v north component of current velocity
w vertical component of current velocity
K_H horizontal diffusion coefficient for temperatnre
K_V vertical diffusion coefficient for temperature
Q' incoming heat energy

t is time and x, y and z are positive eastward and downward, respectively. This equation is integrated with following boundary conditions:

at $z=0$ (sea surface)

$$\begin{cases} Q' = Q_S \\ \rho c_p K_V \dfrac{\partial \theta}{\partial z} = Q_b + Q_h + Q_e \end{cases}$$

at $z=h$ (bottom of the surface layer)

$$\begin{cases} Q' = 0 \\ -\rho c_p K_V \dfrac{\partial \theta}{\partial z} = k'(\bar{\theta} - \theta) \end{cases}$$

Here,

Q_S short wave radiation which is transferred into the water across the sea

surface

Q_b effective back radiation at the sea surface

Q_h sensible heat

Q_e latent heat

$\bar{\theta}$ mean water temperature in the surface layer

θ_h water temperature at the bottom of the surface layer ($z=h$)

Q_S, Q_b, Q_h and Q_e are computed by the method used in the first report of a series of this study (MORIYASU, 1969). In addition, it is assumed that

$$w = \frac{z}{h} w_h ,$$

where w_h is vertical component of current at the bottom of the surface layer and $w_h = \partial h/\partial t$ is taken. This assumption is natural and is adopted in many cases. Then,

$$\int_0^h \frac{\partial \theta}{\partial t} dz = h \frac{\partial \bar{\theta}}{\partial t} + (\bar{\theta} - \theta_h) w_h$$

$$\int_0^h w \frac{\partial \theta}{\partial z} dz = -w_h (\bar{\theta} - \theta_h)$$

are obtained. After these procedures, the next equation is derived:

$$\rho c_p h \frac{\partial \bar{\theta}}{\partial t} = -\rho c_p \int_0^h \left(u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y} \right) dz + \rho c_p K_H \int_0^h \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial x^2} \right) dz$$
$$- k' (\bar{\theta} - \theta_h) + Q_{SA} ,$$
$$Q_{SA} = Q_S - (Q_b + Q_h + Q_e) .$$

Now, another assumption is made between the sea surface temperature θ_0 and the mean temperature of the surface layer, that is,

$$\theta = \alpha \theta_0 .$$

α is a function of time. Then,

$$\frac{\partial \bar{\theta}}{\partial t} = \alpha \frac{\partial \theta_0}{\partial t} + \theta_0 \frac{\partial \alpha}{\partial t}$$

is obtained and the variation of the mean temperature is converted into the variation of the sea surface temperature. Thus, the variation of the sea surface temperature is introduced with some approximations as follows:

$$\frac{\partial \theta_0}{\partial t} = -\theta_0 \left(\frac{1}{\alpha} \frac{\partial \alpha}{\partial t} + \frac{k'}{\rho c_p h} \right) - \left(U \frac{\partial \theta_0}{\partial x} + V \frac{\partial \theta_0}{\partial y} \right)$$
$$+ \frac{Q_{SA}}{\rho c_p \alpha h} + K_H \left(\frac{\partial^2 \theta_0}{\partial x^2} + \frac{\partial^2 \theta_0}{\partial y^2} \right) .$$

Here, U and V are the mean of u and v in the layer, respectively. This equation does not include the effects of vertical motion because of compensation caused by $\int_0^h \frac{\partial \theta}{\partial z} dz$ and $\int_0^h w \frac{\partial \theta}{\partial z} dz$. Though the assumption on α is not supposed to be reasonable in some cases, it is adopted to simplify the model.

This relation requires information on sea surface temperature around the considered point and $U(\partial\theta_0/\partial x)$, $V(\partial\theta_0/\partial y)$, $\partial^2\theta_0/\partial x^2$ and $\partial^2\theta_0/\partial y^2$ are assumed to be dependent on season and not on year. Therefore, these terms are taken constant for individual month independently of year. Thus, a simplified relation

$$\frac{\partial \theta_0}{\partial t} = A\theta_0 + \frac{Q_{SA}}{\rho c_p \alpha h} + C$$

is obtained. Here,

$$A = -\left(\frac{1}{\alpha}\frac{\partial \alpha}{\partial t} + \frac{k'}{\rho c_p h}\right),$$

$$C = -\left(U\frac{\partial \theta_0}{\partial x} + V\frac{\partial \theta_0}{\partial y}\right) + K_H\left(\frac{\partial^2 \theta_0}{\partial x^2} + \frac{\partial^2 \theta_0}{\partial y^2}\right) + \frac{k'\theta_h}{\rho c_p \alpha h}.$$

3. The values of α and h

The relation obtained in the previous section shows that the variation of sea surface temperature is dependent on sea surface temperature and the amount of heat exchange between the sea and the atmosphere. Here, normal values are given to the effects of advection and of diffusion, and then A and C are taken to be constant for individual month. Strictly speaking, α and h in the second term on the right-hand side are dependent on lacation. But, their values are not determined for lack of data. Then, the values for two ocean weather stations, X (39°N, 153°E) and T (29°N, 135°E), are used for areas to the north and to the south of 36°N, respectively. The Western North Pacific Central Water and the Subarctic Pacific Water are in contact with each other around 36°N (SVERDRUP et al., 1942). That is why the critical latitude of 36°N is taken. Normal values of temperature at standard depths for each month are computed by KOIZUMI (1955). Based on them, isopleth diagrams are reproduced for the two stations (Fig. 1). The surface layer is defined as the layer in which seasonal variation of temperature is predominant, and 10°C and 19°C are taken as temperature at the bottom of the surface layer for Stations X and T, respectively. Then, the thickness of the layer (h) and the ratio of the mean temperature to the sea surface temperature (α) are calculated. The results are presented in Table 1. This table also shows $(1/\alpha)(\partial\alpha/\partial t)$.

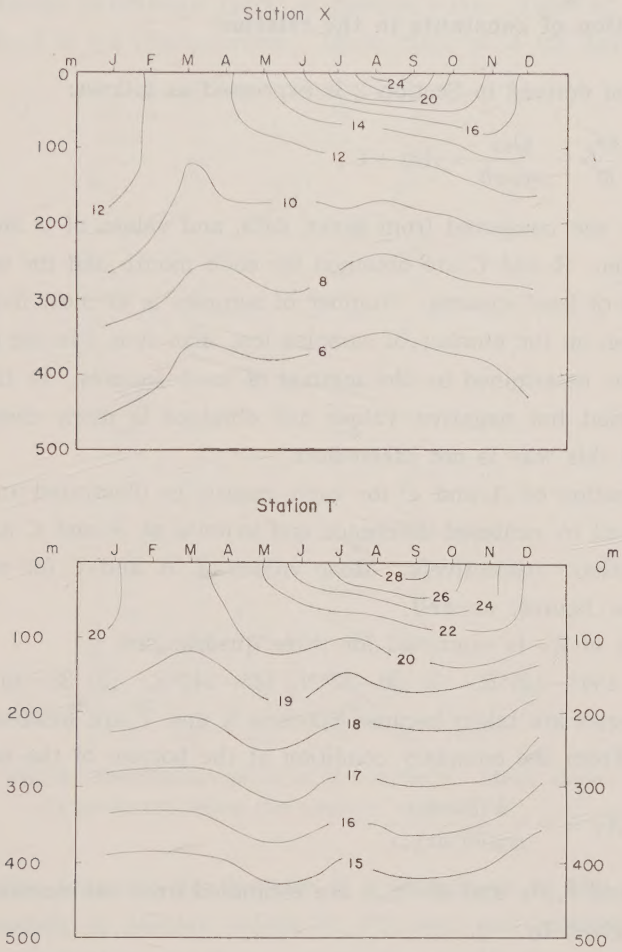

Fig. 1. Isopleth diagrams of water temperature in °C at Stations X and T, based on normal values computed by KOIZUMI (1955).

Table 1. α, h and $(1/\alpha)\,(\partial\alpha/\partial t)$ at Stations X and T.

	Station X			Station T		
	α	h	$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}\times 10^7\,\mathrm{sec}^{-1}$	α	h	$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}\times 10^7\,\mathrm{sec}^{-1}$
March	0.983	120 m	−0.0765	0.991	120 m	−0.0428
April	0.930	160	−0.2614	0.967	150	−0.1317
May	0.857	170	−0.4142	0.925	180	−0.2044
June	0.746	170	−0.4965	0.869	180	−0.2286
July	0.665	180	−0.3829	0.822	140	−0.1854
August	0.614	170	−0.0785	0.790	160	−0.0049

4. Determination of constants in the relation

The relation derived in Section 2 is expressed as follows:

$$\frac{\partial \theta_0}{\partial t} - \frac{Q_{SA}}{\rho c_p \alpha h} = A\theta_0 + C .$$

$\partial\theta_0/\partial t$ and Q_{SA} are computed from given data, and values of α and h in Section 3 are taken. Then, A and C are obtained for each month and for each quadrangle by the method of least squares. Number of samples is at most five and the computation is given up for number of samples less than four. In the previous report, $1/(\rho c_p \alpha h)$ is also determined by the method of least squares. In this attempt, the same way is tried, but negative values are obtained in many cases. This is unreasonable and this way is not taken here.

The distribution of A and C for each month is illustrated in Figs. 2 and 3. $\partial\theta_0/\partial t$ is replaced by centered difference and so units of A and C are (2 months)$^{-1}$, and °C (2 months)$^{-1}$ respectively. Mean values of A and C for each month are inserted in the figures, as well.

Now, value of K_V is examined for three quadrangles:
(1) 30—32°N, 130°—135°E, (2) 30—32°N, 135—140°E, (3) 38—40°N, 150—155°E. These quadrangles are taken because Stations X and T are located in or near the quadrangles. From the boundary condition at the bottom of the surface layer,

$$K_V = - \frac{k'(\bar{\theta} - \theta_h)}{\rho c_p (\partial\theta/\partial z)_{z=h}}$$

is obtained. And $\bar{\theta}$, θ_h and $\partial\theta/\partial z_{z=h}$ are estimated from the normal value for each month. k' is given by

$$k' = - \rho c_p h \left(A + \frac{1}{\alpha} \frac{\partial \alpha}{\partial t} \right),$$

where A, h and $(1/\alpha)/(\partial\alpha/\partial t)$ are known. Thus, value of K_V is estimated for each month. Though the results are not satisfactory and k' is negative in some cases,

Table 2. Vertical diffusion coefficient K_V(g cm^{-1} sec^{-1}) computed for three quadrangles

	February	March	April	May	June	July	August
30—32°N, 130—135°E	*	*	10.118	12.935	24.481	21.131	33.820
30—32°N, 135—140°E	6.692	2.142	10.692	*	25.759	27.781	*
38—40°N, 150—155°E	49.437	*	*	12.852	*	17.416	19.420

* means negative value.

reasonable magnitude is obtained for k' of positive value (Table 2). The distribution of A in Fig. 2 is not characteristic. Mean value of A for April to August is

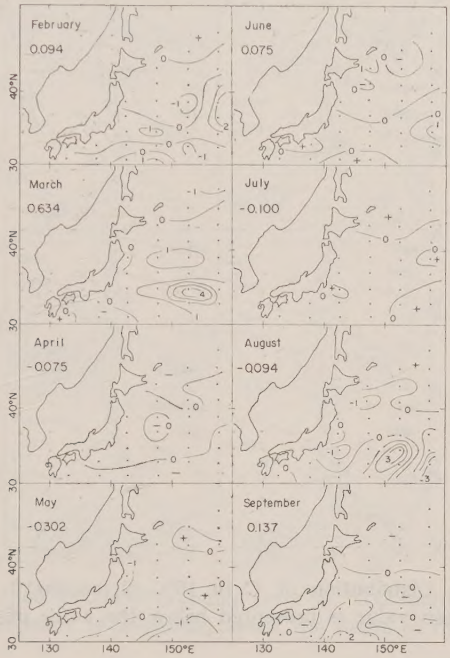

Fig. 2. Distribution of A in (2 months)$^{-1}$. Mean value is presented below the name of month.

negative except for June and the decrease of h contributes to this. It is difficult to show the propriety of positive values for February and September. For $\partial\alpha/\partial t$ and $k'/(\rho c_p h)$ are both positive. This contradiction results from assumption made here or from procedure of the determination. Though the results have such a demerit, following inference is derived. The higher the sea surface temperature is, the more the rising of sea surface temperature is suppressed in the stage of rising temperature in general.

C is mainly the effects of horizontal advection and diffusion and its sign can be positive or negative. Positive sign means the gain of heat from the surroundings and the effects contribute to rising of temperature. Mean value of C is negative for February, March and September, that is, heat energy is lost from the considered area in these months. On the other hand, heat energy is given to the area from April to August. Though the distribution is not characteristic, C is

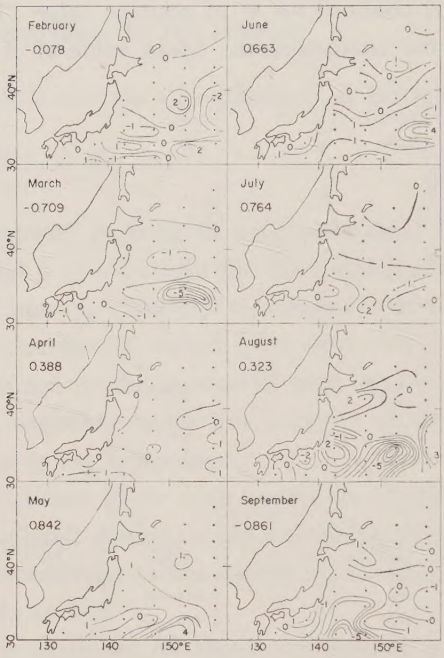

Fig. 3. Distribution of C in 10°C (2 months)$^{-1}$.
Mean value is presented below the name of month.

generally positive in the Kuroshio region and this implies the supply of heat energy due to advection and diffusion.

5. Fittingness of the model

In this section, it is examined how the relation introduced in Section 3 approximates the variation of sea surface temperature. For this purpose, distribution of probable error of the relation is discussed.

The distribution for each month is shown in Fig. 4. The magnitude of probable error is dependent on area and month, but characteristic features are not distinguished. The greatest value is more than 1.0°C (2 months)$^{-1}$ and even practical use is not admitted in such a case. For two quadrangles, 38—40°N, 140—145°E and 42—44°N, 145—150°E, probable error is large in many months and the model is not good to these quadrangles. In the strong current zone of the Kuroshio, the error is small in general. Though there is a difference in the values of α and h between the north and the south of 36°N, this influence is not clear in the

Fig. 4. Distribution of probable error in °C (2 months)$^{-1}$.
Mean value is presented below the name of month.

distribution. Based on the assumption used in the model, the fittingness is supposed to be poor near the polar front where the fluctuation is very complicated. This feature, however, is not found except for near the coast. This is considered to be caused by the scale of area considered here. There is another region of large error around 30—32°N, 140—145°E. The error is of magnitude of 0.4—0.6°C (2 months)$^{-1}$ on an average in most quadrangles.

The mean of probable error for each month is from 0.481°C (2 months)$^{-1}$ in April to 0.688°C (2 months)$^{-1}$ in July and its variation is nearly sinusoidal with a peak in July and a trough in April. This means that the fittingness is poor in summer and probably it is caused by marked variability of various elements in this season.

The dependence of probable error on area and month is noted above and the magnitude is more than 0.4°C (2 months)$^{-1}$ in general. This error is not small and the model used here is not satisfactory. If sea surface temperature for the following month is estimated on the basis of sea surface temperatures in the reference month and the previous month and various meteorological elements in

the reference month, the probable error is of such a magnitude. This indicates the limitation of the simplified model which is constructed on many assumptions.

6. Extended estimation of sea surface temperature

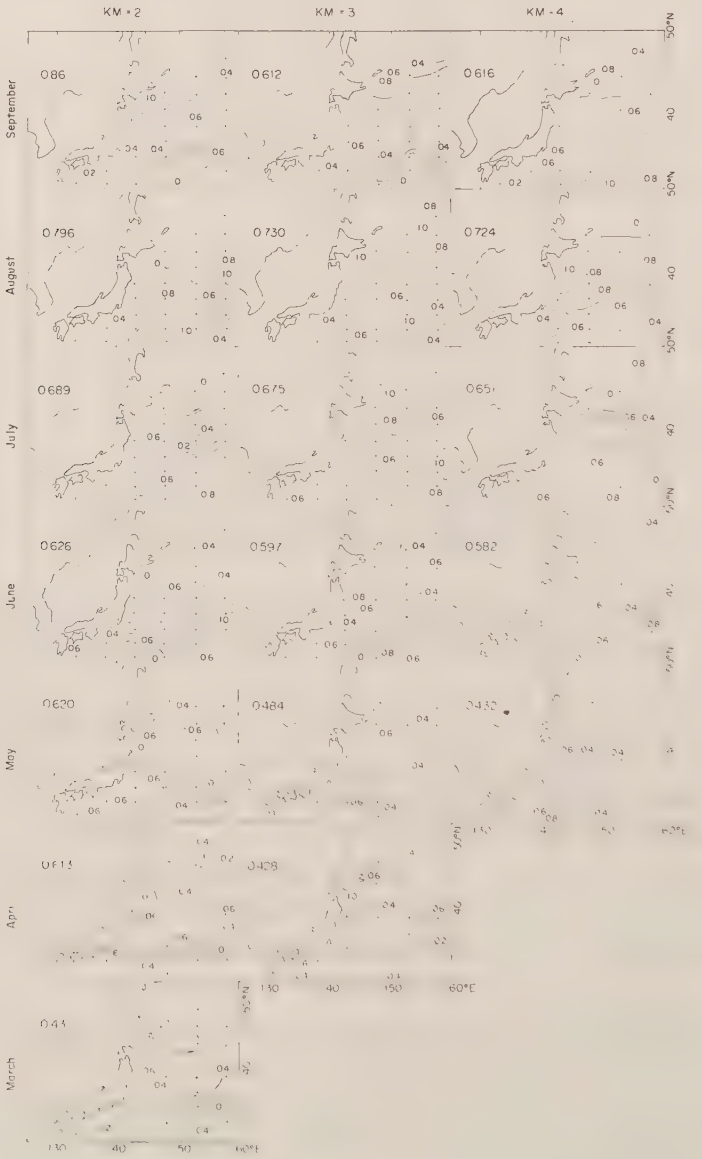

Fig. 5(a)

As stated in the previous section, the model is not sufficient to approximate the variation of sea surface temperature in a month and this is caused by simplified assumptions in the introduction of the model. Though the model has no expected accuracy, it is examined how the model approximates the variation of sea surface

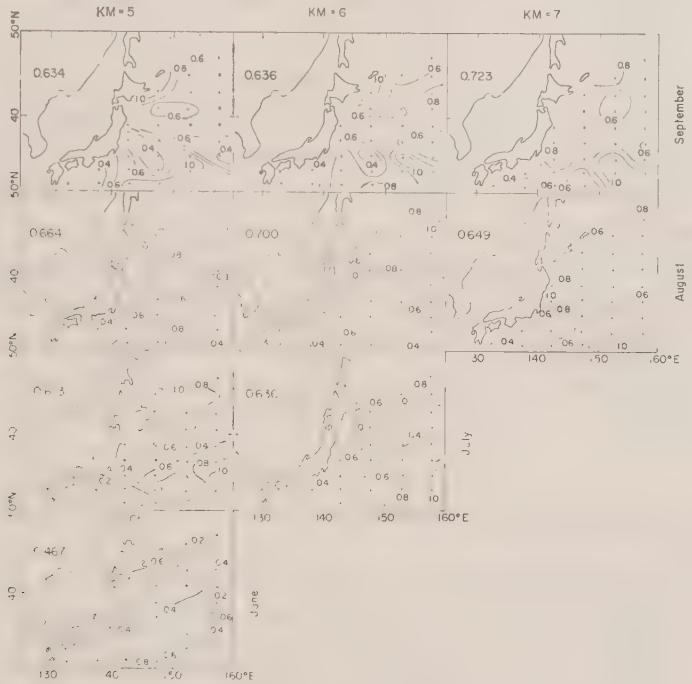

Fig. 5(b). Distribution of the deviation of estimation in °C.
Mean value is presented in the left upper corner of each figure.

temperature for periods longer than one month.

In the trial, starting month is from February (KM=2) to July (KM=7) and sea surface temperatures in the successive months to September are estimated for 1961 to 1965. Here, observed values are given to meteorological elements for individual month. The relation in Section 3 is integrated for given initial temperature corresponding to KM by Runge-Kutta-Gill's method. Such a procedure causes the accumulation of error and the accuracy is supposed to be poorer with increase of the period. This situation is seen in general with some exceptions, which is brought about by mere chance.

Root mean squares of deviations of estimated value from observed value for various KM's and months express the accuracy of the estimation of sea surface

temperature. 0.6745 times this quantity is named the deviation of estimation, hereafter, and its distribution is shown in Fig. 5. The deviation is large in the coastal area of the Northern Japan and in the southeastern part of the considered region, while it is small in the Kuroshio Extension. Though these are general characteristic features in the distribution, its details are dependent on KM and month. Mean value of the deviation for all quadrangles is taken as a measure of approximation and is inserted in Fig. 5. Most values are between 0.4°C and 0.8°C and increase with the period of estimation. For KM=3~6 (starting month is March to June), however, the value for September is less than the value for August. The value is small for May and June, and the model is considered to be useful to these months.

In this trial, initial sea surface temperature is given and meteorological elements in the period of estimation are also given. Therefore, the estimated sea surface temperature must be equal to the observed one if the model is appropriate. The deviation of estimation is not small as shown in Fig. 5 and the model is to be improved in future.

7. Results under assumed conditions

In this model, meteorological elements are taken as input data independent of sea surface temperature. It is useful to estimate the change of sea surface temperature caused by the change of meteorological elements. Here, the estimation is made for the change of cloudiness and wind speed. Value of cloudiness or wind speed in each month is assumed to be larger or smaller by 10% or 20% than observed value and the sea surface temperature estimated under these conditions is compared with one under observed condition for 1961 to 1965.

Decrease in cloudiness makes Q_s larger and then Q_{SA} is larger. Q_b, Q_h and Q_e are also larger due to higher sea surface temperature brought about by increase in Q_S, but the increase is not larger than the increase in Q_S. Therefore, rise of sea surface temperature is supported by decrease in cloudiness and increases with time. On the contrary, the increase in cloudiness suppresses rise of sea surface temperature due to the decrease in Q_{SA}. Change of wind speed has influence on Q_h and Q_e which are proportional to wind speed in the bulk method. The effect of its decrease is considered. Decrease in evaporation is brought about and this contributes to rise of sea surface temperature through the increase in Q_{SA}. If condensation takes place (Q_e is negative), the decrease in wind speed causes the

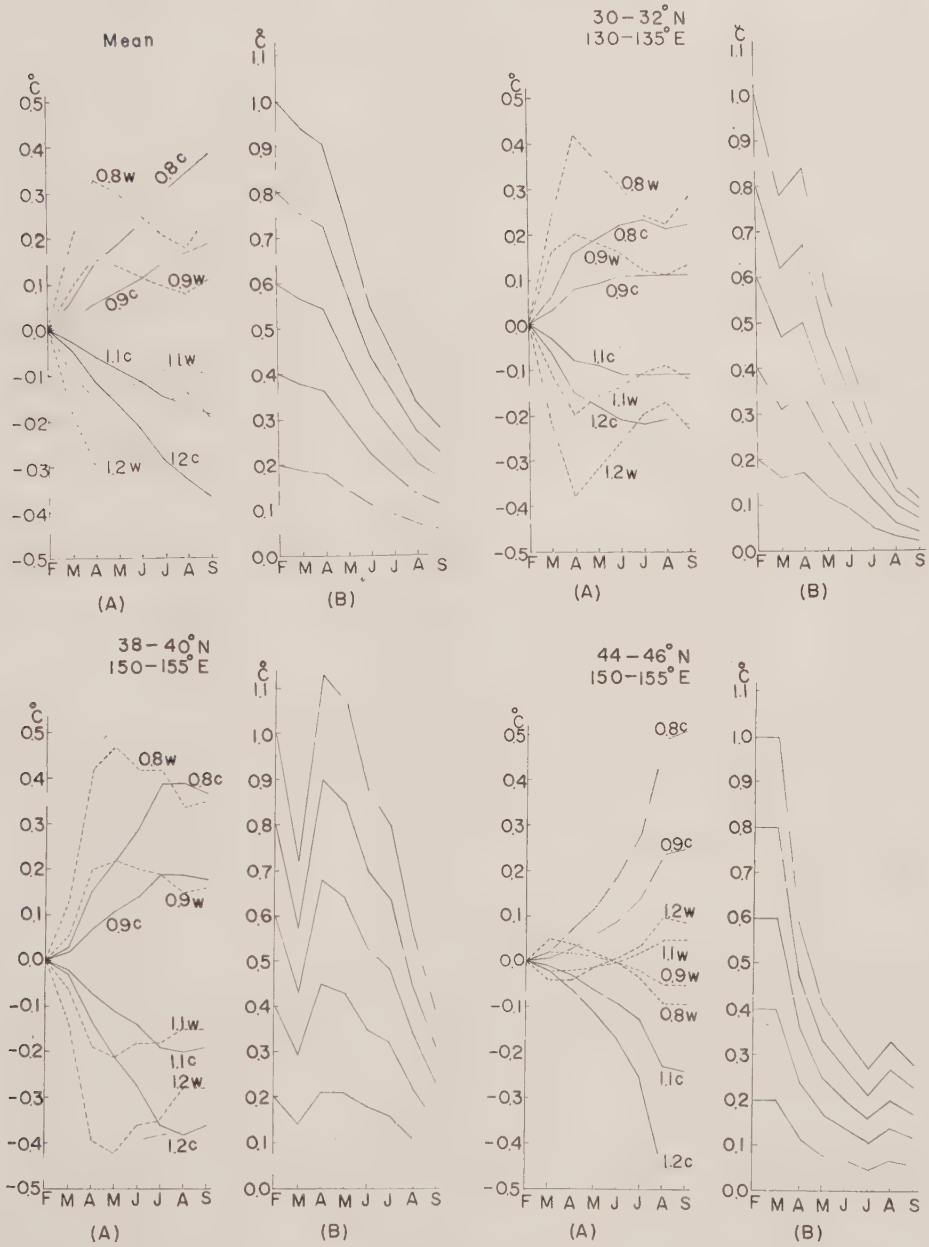

Fig. 6. The effects of cloudiness and wind speed (A), and initial sea surface temperature (B) on sea surface temperature. 0.8C (1.2W) means that cloudiness (wind speed) in the period is smaller (larger) by 20% than observed value.

contrary effect and suppresses rise of sea surface temperature. Here, the latter case is not general. The magnitude of Q_h also decreases in proportion to wind speed in the bulk method. If sea surface temperature is higher (lower) than air temperature, heat loss (gain) in the form of Q_h decreases and then support (suppresses) rise of sea surface temperature through the increase (decrease) in Q_{SA}. This effect is dependent on quadrangle and month for the above reason and its variation is complicated. For increase in wind speed, reverse effects are produced as expected from the bulk method. Fig. 6 shows these effects for three quadrangles and the mean of those for all quadrangles. The value in the figure is the mean of those for 1961 to 1965. For a quadrangle in the northern part, 44—46°N and 150—155°E, an interesting feature is found. The decrease in wind speed supports the rise of sea surface temperature till June, but thereafter suppresses it owing to the decrease in condensation, because dew-point temperature is higher than sea surface temperature.

Next, initial value, the sea surface temperature for February, is assumed to be higher or lower than the observed one and the effects of initial value is estimated in the way shown above. The rise of sea surface temperature is marked in quadrangles in 34—40°N before May and thereafter to the north of 38°N and to the north of 38°N and to the east of 150°E. Examples in Fig. 6 show the effect of initial temperature higher by 0.2—1.0°C than observed one. The effect is supposed to decrease with time and this feature is clear in the mean value. For example, when initial temperature is higher by 1.0°C, the effect for September is only 0.28°C. The decrease in the effect is not simple in general, but even increase is found.

The effect of cloudiness, wind speed and initial temperature is discussed in the above description. Roughly speaking, the effects are expected ones from physical considerations. But, the results are thought to be different from true ones. In this discussion, one of meteorological elements is changed and others are kept unchanged. These elements, however, are dependent on sea surface temperature and then take values different from the observed ones if sea surface temperatures are different from observed ones. Namely, the change of a meteorological element causes the change of other meteorological elements through the change of sea surface temperature. Therefore, the true effects are to be estimated with closer attention to these interactions and the results presented here are only superficial ones.

8. Concluding remarks

Variation of monthly mean sea surface temperature is approximated by a simplified model which is constructed on many assumptions. Since the model is much simplified, sufficient approximation is not expected. But, the results are tolerable ones and this model may be used to estimate mean sea surface temperature in the following month.

In this model, heat exchange between the sea and the atmosphere is taken into consideration and meteorogical elements are used as input data independent of sea surface temperature to compute the amount of the heat exchange. These meteorological elements, however, are related to sea surface temperature and this assumption should be revised. Therefore, it is necessary to construct a model which is made up of the sea and the atmosphere and in which air-sea interactions are considered. From this point, description in the last section is not reasonable in the strict sense of the word and only gives rough estimates on the effects of meteorological elements and initial sea surface temperature. Furthermore, extended estimation of sea surface temperature should be based on such a model.

Acknowledgements

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北西太平洋の月海面水温の変動について (IV)

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前報で南方定点の旬海面水温の変動を再現するためのモデルを作ったが，このモデルを少し改めて北西太平洋の月海面水温の変動に応用した。このモデルでは海面水温の変動が考えている場所の海面水温と海洋・大気間の熱交換量の一次式として表わされるものとし，水平方向の移流・拡散の効果は月によって変化するが，年による変化はないものと仮定している。用いたモデルはこのように非常に簡略化されているので，その近似は満足できるものではないが，続く月の海面水温の概略の推定には使用できそうである。更にこのモデルを使って気象要素の変化が海面水温にどの程度の影響を与えるかについて，雲量と風速を例にとって，その大体の見積りを試みた。

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On the statistics and relations of the unusual sea level changes to oceanic and atmospheric conditions

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Japan Meteorological Agency

(Received September 30, 1973)

Abstract: An investigation on unusual sea level changes occurred along the south coast of Japan in 1971, was made. The daily tidal data in the last 11 years at 12 tide stations along the south coast of Japan are used for the analyses of unusual sea level changes. Those continuing for relatively short period (2 to 3 weeks) are investigated statistically and in the points of their relations to oceanic and atmospheric events with the use of deviations of observed daily mean sea level from the predicted.

Many of the unusual changes investigated are found to be closely related to the wind blowing in parallel to the south coast of Japan. Easterlies heave up and westerlies lower the sea levels along the south coast of Japan. These wind fields make up Ekman trasport perpendicular to the coast at first which is soon affected by the shore and reaches equilibrium within a few days, and unusual sea level changes along the coast are established at last.

1. Introduction

Unusual high sea level changes continued for about a few weeks from the 1st of September, 1971 (see fig. 1), and many cities on the low lands along the south coast of Japan and the Seto Inland Sea were flooded. The deviation of sea level from the undisturbed was sbout 20 to 30cm, and was much smaller than that due to storm surges or tsunami. However, as the phenomenon continued much longer than other unusual sea level changes ever experienced, it gave an unquieting effect to the people who had become very thin-skinned to the change of their environment.

This unusual phenomenon was investigated by many researchers, phenomenologically and theoretically—COMMITTEE for UNPREDICTED FLOODS 1972, RESEARCH GROUP for UNPREDICTED FLOOD 1972, SHOJI 1973, IIDA et al. 1973, YOSHIDA et al. 1973, TERAMOTO et al. 1973, NITANI 1973, SUDA 1973, SUGINOHARA 1973, ENDOH 1973, MIYAZAKI 1973, AMANO 1973, ISOZAKI 1973, MIYAZAKI et al. 1973 and so on. These investigations, except IIDA et al. 1973, treated positive unusual sea level

changes, but the negative ones are very important and useful in order to study the causes of them. In this report both the positive and negative cases are treated.

The hourly tide data in recent twelve years (1961-1972) from 12 tide stations along the coast of Japan, are used to pursue the causes of unusual sea level changes with comparison to meteorological and oceanographical data (see fig. 2). At first we define the deviation of sea level from usual—unusual sea level change—as the difference between the observed and the predicted sea level. All the solar, meteorological and geophysical or crustal events can be the cause of such deviations of sea level. These give momentum or density changes in the sea waters in some case, which affect the coastal sea level. Some of meteorological events, such as heating, cooling, evaporation and precipitation, change the water density, which results in the sea level change on the coast. Eaustatic change of sea level corresponds to climatological change of the earth. Among the geophysical events, earthquakes raise very short period change of sea level—tsunami—changes of the axis of the earth's rotation, for example nutation of the earth, stir up small periodic change of about a year or more, and movement of the earth's crust is the cause of a long-term change in sea level. Oceanographical events, like the change in the direction of the stream sxis of the Kuroshio, invasion of the warm water masses to the coastal area, etc., are sure to be affected by the meteorological phenomena of large or medium scale.

The features of the unusual rise of sea level in September 1971 which continued for a week or more, were not oscillatory phenomenon and much smaller than storm surge which is not oscillatory. In order to distinguish such sea level changes of medium time scale from other shorter and longer period changes, it is necessary to use daily mean sea level data and exact predicted sea level changes. In order to filter out the longer period changes exactly, the harmonic constants of the long period constituents, SA and SSA calculated from the hourly data of the year were used and as the other harmonic constants for shorter period constituents the mean values during 2 to 5 years period including the year 1971 were used.

Deviation of sea level is calculated with the following formula,

$$\text{Deviation of sea level} = (\text{Observed} - \text{Observed yearly mean}) - (\text{Calculated} - \text{Calculated yearly mean}) \quad (1)$$

Local pressure effect is eliminated by the hydrostatic assumption, so

$$\text{Deviation with pressure correction} = \text{Deviation of sea level} + (\text{Sea surface pressure} - \text{Standard pressure}) \quad (2)$$

where mean pressure of the month used as the standard pressure for convenience's sake.

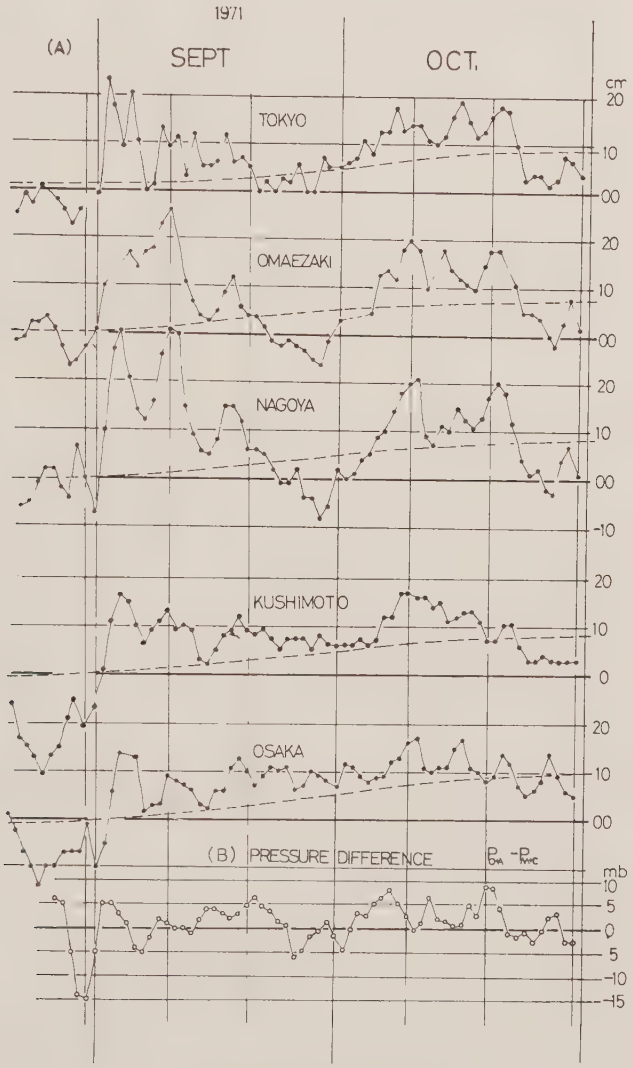

Fig. 1–A. Deviations of sea level from usual (solidline); deviation with pressure correction. (brokenline), 31 day running mean of daily mean pressure.

Fig. 1–B. Pressure difference ($P_{O+A}-P_{M+C}$), where $P_{O+A}=(P_{Omaezaki}+P_{Aburatsu})/2$ and $P_{M+C}=(P_{Minamidaito}+P_{Chichijima})/2$.

Fig. 2. Tidal stations •

It is very hard to eliminate local and short period wind effect, but the effect appears as an isolated peak or trough in the graph of the daily mean deviation of sea level, and is easily discernible.

2. Unusual sea level change with the duration of a few weeks or more

With the use of deviation data of sea level obtained as mentioned in § 1, the following results are obtained, where the unusual sea level change is defined as such that the maximum deviation is beyond +15cm or −10cm.

(a) Timing of occurrence (see fig. 3)

(i) Year to year distribution of the number of occurrence is nearly homogeneous, ranging twice to five times a year, but the number is a little smaller in 1965, 68, and 69.

(ii) Monthly distribution of positive deviation is homogeneous, too, but occurrences are a little fewer in December and January, while negative deviations are apt to occur in July and August.

(b) Spatial tendency of occurrence (see fig. 3)

(i) The occurrence is often the simultaneous events along the south coast of Japan.

(ii) For the south coast of Japan, the amount of deviation is the largest along the coast of the Tokai district, next to this is along the coast west of the Kii Peninsula and the smallest is along the south coast of the Kanto District.

(iii) The occurrence of unusual sea level change with large deviation, can seldom be seen along the west coast of the Kyusyu District and along the coast of the Japan Sea. As exceptions, positive deviation is seen at the entire stations treated in August 1966 and negative case in July 1971.

Fig. 3. Frequencies of unusual sealevel change with pressure correction ● above +25 cm, ○ +15~25 cm, ▲ below −20 cm and △ −10~−20 cm. SGO; Saigo, MSM; Misumi, ABT; Aburatsu, TSZ; Tosashimizu, MYM; Matsuyama, TNN; Osaka, KMT; Kushimoto, NGY; Nagoya, OMZ; Omaezaki, UCU; Uchiura, OSM; Osima and TKY; Tokyo.

(iv) Deviations are apt to become larger at the stations in the eastern part of the Inland Sea and at Nagoya which is in a shallow and semi-enclosed bay.

(v) The duration of unusual sea level change is longer in the Inland Sea.

(c) Statistics of duration and magnitude without pressure correction.

The following facts can be read out from the distribution of frequencies concernig the duration with the same sign of the deviation and the magnitude of its peak value during the occurrence (see Table 1 and fig. 4)

(i) The rate of occurrence of unusual sea level change which has the absolute value of maximum deviation larger than 10cm and the duration of a week or more, is 10 to 12% of the total number of occurrence along the south coast of Japan and 6% at Saigo in the Japan Sea.

(ii) As to the duration shorter than a week, negative ones occur more frequently than positive ones, while positive ones are more frequent for those with the

Table 1. Frequency distributions of sea level changes concerning with duration and maximum deviation, (a) Oshima, (b) Omaezaki, (c) Nagoya, (d) Kushimoto, (e) Osaka, (f) Aburatsu, (g) Misumi and (h) Saigo.

(Duration in days) (a) OSHIMA (OKADA)

Days	1	2	3	4,5	6,7	8,9	10～12	13～17	18～22	23～27	28～32	33～37	38～42	43～	Total Nos.
−Total Nos.	95	96	70	54	28	12	13	10	4	2	1			1	386
Maximum values in cm for negative case															
−32～															
−28～−32															
−23～−27											1				1
−18～−22			1	2			3	1	1	1				1	10
−15～−17			1	1	1	1	1	3	·2	1					11
−12～−14			5	6	7	3	4	2							27
−10,−11		3	9	6	3	·5	2	1	1						30
− 8,− 9	1	6	17	·13	7	2	2	2							50
− 6,− 7	2	21	·16	10	·8		1	1							59
− 4,− 5	19	26	10	·15	2	1									73
− 1,− 3	·44	·32	1	1											78
− 1	29	8	10												47
0	248	46	1	3											298
Maximum values in cm for positive case															
1	38	3	2												43
2,3	·40	20	8	1											69
4,5	25	·22	8	7	2										64
6,7	16	19	·13	·13	5	3									69
8,9	8	15	9	8	·8		2	1							51
10,11	1	6	4	8	3	·5	1	2							30
12～14	2	4	·6	·11	4	4	2	·4							37
15～17		3	2	2	·9	4	1	2							23
18～22	1			4	3	1	·3	·4	3	1					20
23～27			1					1		1					3
28～32						1	1	1							3
33～37											1				1
+Tota lNos.	131	92	53	54	34	18	10	15	3	2	1				413
Total Nos.	474	234	124	111	62	30	23	25	7	4	2			1	1097

(Duration in days) (b) OMAEZAKI

Days	1	2	3	4,5	6,7	8,9	10～12	13～17	18～22	23～27	28～32	33～37	38～42	43～	Total Nos.
−Total	85	88	61	58	30	20	15	17	6		1	1			392
Maximum values in cm for negative case															
−33～−37												1			1
−28～−32															
−23～−27															
−18～−22				1		1	4	3	2						11
−15～−17			1	4	2	1	2	2	1		1				14
−12～−14			8	5	6	5	6	6	3						39
−10,−11		3	1	·11	·10	6	2	4							37
− 8,− 9		5	10	8	6	3		2							34
− 6,− 7	2	8	14	13	4	2	1								44
− 4,− 5	13	·35	·19	·14	1	1									83
− 2,− 3	37	30	8	2	1	1									79
− 1	43	7													50
0	280	27	9	4											320
Maximum values in cm for positive case															
1	38	2													40
2,3	·45	23	2	1											71
4,5	17	·25	·7	4	1										54
6,7	11	21	·7	6	3	2	1								51
8,9	5	12	6	·8	·6	2	1								40
10,11	1	6	5	6	5	1	3	·3	1						31
12～14	2	5	7	4	5	1	5	1							30
15～17			5	3	5		2	·2	4						21
18～22		1	2	3	1	5	2	1	1						16
23～27		2	1	1	2	2	4	1	1		1	1			16
28～32					1			1							2
33～37						1			1	1					3
+Total Nos.	119	97	42	36	29	14	18	9	8	1	1	1			375
Total Nos.	494	212	112	98	59	34	33	26	14	1	2	2			1087

(Duration in days) (c) NAGOYA

Days	1	2	3	4,5	6,7	8,9	10～24	13～17	18～22	23～27	28～32	33～37	38～42	43～	Total Nos.
−Total Nos.	98	95	74	71	38	20	17	17	4	2	1				437
Maximum values in cm for negative case															
−23～−27								1							1
−18～−22			1	3	3		5			1					13
−15～−17				5	5	3	5	3	2	1	1				25
−12～−14	1	1	8	·14	7	5	4	·6	2						48
−10,−11		·10	·16	12	7	·6	1	1							53
− 8,− 9		8	9	8	·9	2		1							37
− 6,− 7	8	18	13	·13	6	3	2	4							67
− 4,− 5	14	24	22	12	1	1									74
− 2,− 3	36	·30	5	4				1							76
− 1	·39	4													43
0	271	49	2	2											324
Maximum values in cm for positive case															
1	31	3	1												35
2,3	49	17	5												71
4,5	34	19	·8	3	1	1									66
6,7	10	·20	5	8	1	1									45
8,9	10	15	4	9	4	2	2								46
10,11	4	9	10	·10	·9	·5	1								48
13～14	2	·13	·11	9	4	3	4	1							47
15～17	2	3	3	3	5	·4	·5	·5	1	1		1			33
18～22			3	1	.6	3	2	1	2						18
23～27		2	3	2	6	2	1	2							18
28～32		2	1	3				1	3	1					11
33～37		1					1		1						3
38～42									1						1
43～47		1													1
48～			1			1									2
+Total Nos.	142	105	55	48	36	22	16	10	8	2		1			445
Total Nos.	511	249	131	121	74	42	33	27	12	4	1	1			1206

(Duration in days) (d) KUSHIMOTO

Days	1	2	3	4,5	6,7	8,9	10～12	13～17	18～22	23～27	28～32	33～37	38～42	43～	Total Nos.
−Total Nos.	109	94	59	78	41	16	11	14	4			1		1	428
Maximum values in cm for negative case															
−28～−32														1	1
−23～−27															
−18～−22				3	4	2	2	2							13
−15～−17		1	5	10	5	3	3	3	2			1			33
−12～−14			5	·14	·10	4	3	5	2						43
−10,−11			9	13	8	4	1	2							37
− 8,− 9	1	·15	13	·16	7	3	1	2							58
− 6,− 7	3	9	·14	9	6		1								42
− 4,− 5	21	·35	8	6	1										71
− 2,− 3	39	33	5	7											84
− 1	·45	1													46
0	203	31	4												238
Maximum values in cm for positive case															
1	31	3	1			1									36
2,3	·36	15	12												63
4,5	22	·32	·19	1	3										77
6,7	11	19	10	·10	·5	1									56
8,9	2	11	·13	9	3	2									40
10,11	3	4	6	7	3	·5	1								29
12～14	1	·7	5	7	·6	2	·6	3		1					38
15～17		3	4	5	2	·5	2	5	1	1					28
18～22	1		3	3	5	4	5	5		1	1				28
23～27					5	1		3	1						10
28～32					1			2		1		1			5
33～37									1						1
38～42															
43～							1			1					2
+Total Nos.	107	94	73	42	33	21	15	18	3	5	1	1			413
Total Nos.	421	219	136	120	74	37	26	32	7	5	1	2			1081

(Duration in days) (e) OSAK

Days	1	2	3	4,5	6,7	8,9	10～12	13～17	18～22	23～27	28～32	33～37	38～42	43～	Total Nos.
−Total Nos.	117	103	76	69	46	18	17	13	3	1					463
Maximum values in cm for negative case															
−23～−27						1									1
−18～−22			1		3	·4	3	3	1						15
−15～−17	1		3	3	6	2	5	.5	1						26
−12～−14		2	6	·12	·10	·4	5	2	1	1					43
−10,−11	2	10	12	9	·10	3	1	2							49
− 8,− 9	3	11	15	14	6	3	1	1							54
− 6,− 7	5	18	·21	·16	·8	1	1								70
− 4,− 5	19	.34	13	11	3		1								81
− 2,− 3	·51	24	3	4											82
− 1	36	4	2												42
0	288	40	6	1											335
Maximum values in cm for positive case															
1	35	4													39
2,3	·45	17	6												68
4,5	29	15	11	8	1										64
6,7	14	·23	·13	5	2	1									58
8,9	9	12	6	·16	3	2	1								49
10,11	3	·14	·11	6	·6	2	3	2							47
12～14	2	11	8	8	6	·6	4	3	1			1			50
15～17	1	2	8	6	5	3	4	2							31
18～22	1	3	5	·9	4	3	3	·6	2	1					37
23～27				2	1		2	2			1				8
28～32			1	1	1			1	1						5
33～37	1			1		1		1	1						5
38～42									1						1
43～					1										1
+Total Nos.	140	101	69	62	30	18	17	17	6	1	1	1			463
Total Nos.	545	244	151	132	76	36	34	30	9	2	1	1			1261

(Duration in days) (f) ABURATSU

Days	1	2	3	4,5	6,7	8,9	10~12	13~17	18~22	23~27	28~32	33~37	38~42	43~	Total Nos.
−Total	63	64	55	77	33	16	22	12	5	4	1		1		353
Maximum values in cm for negative case															
−23 ~ −27											1				1
−18 ~ −22				1			2			1					4
−15 ~ −17				2	2	4	4		1	1					14
−12 ~ −14			1	1	·6	4	4	·6	·4	1			1		28
−10, −11			5	11	4	4	·7	4		1					36
− 8, − 9		2	6	11	·9	4	4	2							38
− 6, − 7		7	11	·28	7		1								54
− 4, − 5	7	22	·18	22	4										73
− 2, − 3	20	·22	14	1	1										58
− 1	·36	11													47
0	272	52	11	2											337
Maximum values in cm for positive case															
1	·32	5													37
2, 3	29	·25	7	4	1										66
4, 5	10	20	·14	8	2										54
6, 7	5	11	5	8	6	1	1								37
8, 9	1	3	6	·12	·6	1	4	1	1						35
10, 11		3	5	7	6	3	4								28
12 ~ 14				5	5	·8	7	·5	1	3	1				35
15 ~ 17			2	4	2	1	·9		3		1				21
18 ~ 22				4	4	3	1	3	3						18
23 ~ 27				1	1	1		2		2					7
28 ~ 32						2	1	1							4
33 ~ 37								1							1
38 ~ 42					1			1							2
43 ~ 47				1											1
48 ~				1											
+Total Nos.	77	67	39	55	34	20	26	14	10	3	2				347
Total Nos.	412	183	105	134	67	36	48	26	15	7	3		1		1037

(Duration in days) (g) MISUMI

Days	1	2	3	4,5	6,7	8,9	10～12	13～17	18～22	23～27	28～32	33～37	38～42	43～	Total Nos.
−Total Nos.	85	90	59	60	38	28	10	16	3						389
Maximum values in cm for negative case															
−23～−27					1										1
−18～−22								2							2
−15～−17				1		1	1								3
−12～−14		1	1	2	6	·9		5	2						26
−10,−11		1	2	·9	7	7	4	4							34
− 8,− 9		6	4	7	·12	·9	2	4	1						45
− 6,− 7	1	15	14	·26	9	2	3	1							71
− 4,− 5	12	24	·21	8	2										67
− 2,− 3	·41	·36	16	6	1										100
− 1	31	7	1	1											40
0	297	49	18	2											366
Maximum values in cm for positive case															
1	·50	8	1	1											60
2,3	47	·24	3	2											76
4,5	16	17	9	6	3	1									52
6,7	7	11	·12	·11	2	2									45
8,9	4	10	6	7	7	·6	4								44
10,11	2	1	6	·15	·11	3	1	2	1						42
12～14		3	5	4	5	3	·6								26
15～17			3	6	1	2	2	·5	3						22
18～22			1	4	1	3	1	2			1				13
23～27				1		1	1		1						4
28～32					1										1
33～37												1			1
38～															
+Total Nos.	126	74	46	57	31	21	15	9	5		1	1			1
Total Nos.	508	213	123	119	69	49	25	25	8		1	1			1141

(Duration in days) (h) SAIGO

Days	1	2	3	4,5	6,7	8,9	10～12	13～17	18～22	23～27	28～32	33～37	28～42	43～	Total Nos.
−Total Nos.	141	135	86	76	47	27	8	4	1	1					526
Maximum values in cm for negative case															
−28～−32						1									1
−23～−27					1	3									4
−18～−22				5	1	3		1							10
−15～−17		1	2	4	4	·8	1	2	1	1					24
−12～−14	1	5	8	9	·14	6	·7	1							51
−10,−11	1	9	17	16	8	4									55
− 8,− 9	4	13	18	17	8	2									62
− 6,− 7	5	23	·19	·18	8										73
− 4,− 5	22	37	10	6	2										77
− 2,− 3	·56	·41	12	1	1										111
− 1	52	6													58
0	347	62	9	4											422
Maximum values in cm for positive case															
1	34	7	3												44
2,3	·60	·32	8	2											102
4,5	27	30	11	9	1										78
6,7	9	28	·19	12	2	3									73
8,9	2	25	11	·20	·10	2									70
10,11	1	4	11	11	7	·4	2	3							43
12～14	1	2	7	·17	·13	3	2	2	2						49
15～17		3	7	6	10	2	4	3	1						36
18～22			3	8	3	3	·5	1							23
23～27				3		2									5
28～32				1			1								2
+Total Nos.	134	131	80	89	46	19	9	3							525
Total Nos.	622	328	175	169	93	46	22	13	4	1					1473

duration longer than a week.

(iii) As to the duration of a few days to a week, frequency distribution of of occurrences is seemed to show bimodal distrbution. The maximum of the frequency distribution appears where the maximum deviation is 5 to 6 cm and 10 to 12 cm in absolute value.

(iv) Frequencies of occurrence of negative deviations are apt to concentrate in the smaller part of the absolute value of deviation than those of the positive. In the negative case, one half of the total occurrence is in the part larger than 5 to 8cm. The maximum of frequency of occurrence seems to appear at a little smaller value for negative deviation than for positive one.

(v) As to the duration, 50% of the total have the duration shorter than a few day and 25%, longer than 4 to 5 days.

(vi) The maximum of frequecy shifts to the larger part of deviation axis, as the duration of the events increases.

(vii) Total number of occurrences is 770 to 930 per ten year along the coast of south Japan and 1051 at Saigo on the Japan Sea, which indicates that the short term events are apt to occur more frequently at Saigo

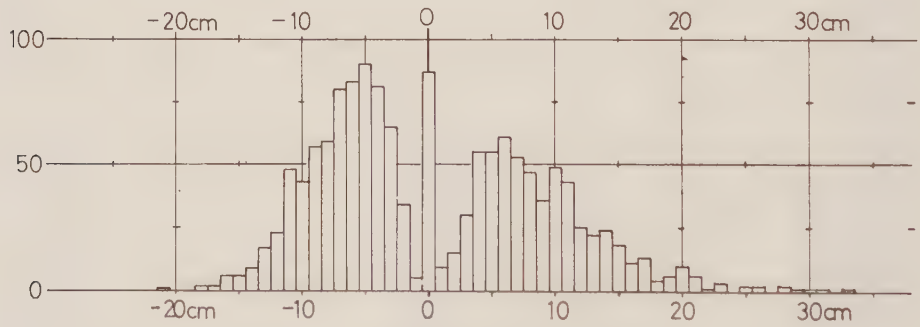

Fig. 4. Frequency distribution of sea level changes continuing for 3 days at the stations.

(viii) The numbers of occurrences for positive and negative ones are nearly the same at all the stations.

(d) The characteristics of sea level deviation (figs. 5)

(i) Appearance and disappearance of unusual sea level change are usually very abrupt (witin 2 to 3 days). It seldom shows gradual appearance and disappearance.

(ii) We can often find superposed oscillations with the period of 4 to 7 days, and their amplituds are larger than in the undisturbed case.

(iii) The date of appearance or disappearance of unusual sea level change is the earliest at the easternmost station and the latest at the westernmost station along the south coast of Japan, and the peaks or troughs due to the small superposed oscillations show the same tendency. The difference between the dates of appearance at Omaezaki and at Aburatsu is 4 to 5 days. If the disturbances migrate westwards, their speeds become 80 to 100 nautical miles a day or 3 to 4 knots.

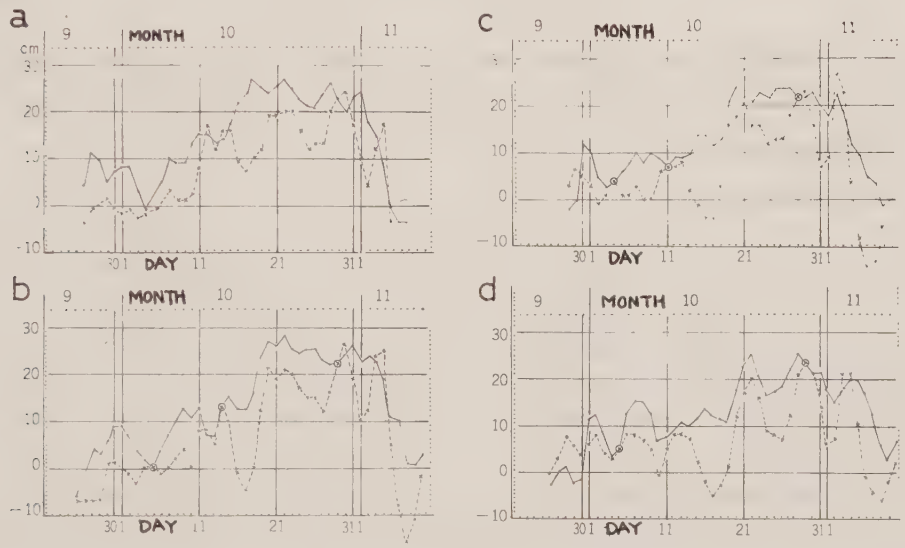

Fig. 5. Daily mean deviations of sea level in October, 1962 at Omaezaki (a), Kushimoto (b), Tosashimizu (c), and Aburatu (d). Solid line; daily mean deviation and broken line; that with pressure correction.

(e) Atmospheric and sea conditions during unusual sea level change

(i) In many cases, it is possible to find some changes of the axis of the Kuroshio. There are, however, some cases in which no corresponding change of the Kuroshio can be seen.

(ii) Westerly currents are observed along the coast from the Izu Peninsula to the Kii Peninsula in many of the cases when positive deviation of sea level is in existence and *vice versa* (see fig. 6).

(iii) In many of the cases when negative deviation of sea level is seen, negative departure of coastal sea surface temperature from normal is taking place,

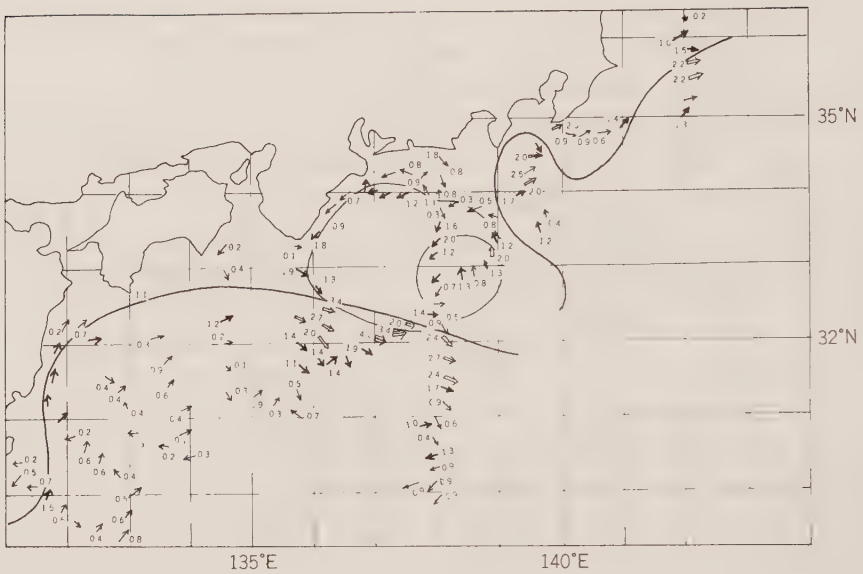

Fig. 6. Surface currents in kt. in October 10 to November 13, 1962.

but in the cases of positive deviation, no definite relation can be found regarding the departure of coastal temperature.

(iv) No special relations are found with respect to typhoons whose tracks resemble to that of the typhoon 7123, or, more simply, to the fact whether typhoons exist or not around Japan.

(v) When unusual sea level change is taking place, winds parallel to the south coast of Japan often prevail south of the Japanese Islands, that is, nearly zonal pressure distribution is continuing for a longer time, or more intensely than usual.

Easterly wind corresponds to positive deviation of sea level and *vice versa*.

(vi) Meridional pressure gradient 2 or 3 days prior to the event shows very good correspondence to unusual change of sea level (see figs. 1 and 7).

3. Concluding remarks

(i) One important cause of the unusual sea level change, is the prevailing wind field parallel to the coast. Parallel component of wind to the coast carries the surface water towards the coast or off the coast, which heaves up or puts down the sea level at the coast. Speaking in detail, it takes about 1 pendulum day (2 day at 30°N and 1.4 days at 45°N) for the Ekman layer to be established after the wind started to blow. Then the Ekman transport carries

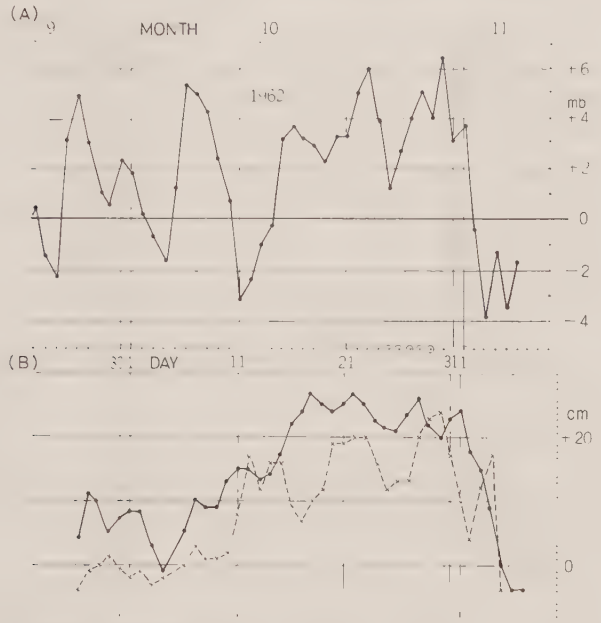

Fig. 7–A. Pressure difference ($P_{O+A}-P_{M+H}$), where $P_{O+A}=(P_{Omaezaki}+P_{Aburatsu})/2$ and $P_{M+H}=(P_{Minamidaito}+P_{Hachijo})/2$.
Fig. 7–B. Deviation of sea level in October 1962 at Omaezaki

surface water to the left facing downstream. This carried water is affected with the coast and an equilibrium state is achieved in a time characteristic to the system which is supposed to be a day or two. In this equilibrium state, upwelling (due to westerlies) or sinking (due to easterlies) of water is seen along the coast, and at the same time the flow parallel to the coast is set up due to the gradient of sea surface perpendicular to the coast. As the result of the above-mentioned theory the final equilibrium state is reached within a few days from the time it started to blow, which will explain the facts mentioned in (a)-(v).

The relation of sea level change to coastal temperature change mentioned in (e)-(iii), will be explained as follows. Negative deviation of sea level is considered to correspond to the upwelling along the coast, which brings cold water from the deeper layer, but in positive case there is no chance to warm up the coastal water very much.

The facts that the outset and end of unusual sea level change and the peaks and troughs of superposed oscillations occur earlier in the eastern part of the south coast of Japan, explained in (d)-(iii), and the deviation is the largest along the coast of Tokai District in (b)-(ii), must be surveyed in later chance.

(ii) Seasonal variation of the occurrence of unusual sea level change in (a)-(ii), can be explained with that of the surface pattern of pressure and the occurrence of parallel wind field to the coast south of Japan.

In February and March, surface pressure pattern of winter type becomes weaker and the continental high stretches itself out to northern Japan, around the southern margin of which lows are apt to move eastwards. If the strech-ing high pressure area shifts southwards, north-high and south-low pressure pattern appears south of Japan, which results in easterly wind field, and positive deviation of sea level is apt to occur. In order that the axis of high pressure area shifts northwards and westerly wind field appears south of Japan, it is necessary for the high pressure area shifts northwards in an larger extent. Such a case is seldom realized.

In April, highs and lows migrate eastwards one after the other regularly in comparatively short intervals and there are no ways to establish prevailing wind field south of Japan.

In May and June, the Ogasawara high develops and a stationary front is stagnant just south of Japan. In case the high does not develop sufficiently and the front shifts southwards, easterly wind field and resulting positive deviation of sea level are prone to appear south of Japan.

In July and August, the Pacific high develops and covers the Japanese islands with its western margin. In case the Pacific high does not develop enough and inclines southwestwards, westerly wind field prevails south of Japan and negative deviation is apt to occur. Typhoons or tropical cyclones strengthen the effects when they move very slowly along the front or stay for a long time, as was seen in 1967 and 1972.

In September, October and November, there are such phenomena as to raise positive deviation of sea level, that is, northwards shifts of travelling highs, continuation of north easterly wind, etc.

In December and January, surface pressure pattern becomes stable—winter type.

(iii) The cause of unusual sea level change is explained with the parallel wind field to the coast south of Japan qualitatively in many cases. Adding to this a strong stream like the Kuroshio flowing along the coast, may affect the coastal sea level through the change of stream conditions—strengthening or weakening, or broadening or meandering—by the parallel wind field over the stream.

Physical meanings of the results of the statistics of occurrence will be studied

in future together with those with pressure correction.

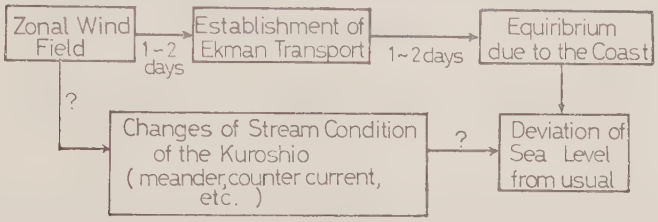
Zonal Wind Field
1~2 days
Establishment of Ekman Transport
1~2 days
Equiribrium due to the Coast
?
Changes of Stream Condition of the Kuroshio (meander, counter current, etc.)
?
Deviation of Sea Level from usual

Fig. 8. Mechanism of unusual sea level changes

Acknowledgement

The authors wish their hearty thanks to professor K. Yoshida, Drs. J. Masuzawa, M. Miyazaki and I. Isozaki for many useful advice and encouragements.

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The Oceanographical Magazine, Vol. 25, No. 1 (1973)

異常潮位の統計および海象　気象との関連について

飯田隼人および岡田正己

（気象庁）

潮位偏差を比較的短期間（2・3週間程度）続くものを取り出し，正および負の異常潮位と分け，気象および海象との対比から原因の究明発生の統計等に関する調査を行った。この程度の潮位異常の原因としては岸に平行の風による海水の吹寄せおよび吹き払い効果が重要である。東がかった風は正の，西がかった風は負の異常潮をおこす。また大きな異常潮は東海地方でおきることが多いなどから見て黒潮も重要な役割を果していることが考えられる。

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Report on the abnormally high storm surge in Tosa Bay

RESEARCH GROUP for the Tosa Bay Storm Surge

Japan Meteorological Agency

(Received September 30, 1973)

Abstract: In the morning of August 21st, 1970, a medium size typhoon called 7010 or Helen attacked the bay of Tosa and severe storm surge occurred along the coast of the bay, especially severe in the innermost part. Although the typhoon was of medium size and the storm was not so severe, the storm surge became the severest in the history of the district. The deviation of the observed sea level from the calculated sea level are much higher than the estimated deviation with a storm surge formula which is used in routine at the weather station of Kochi City and is said to show very well fitting to the past typhoon data. All the numerical experiments have failed to simulate the sea level changes during the storm surge due to the typhoon 7010, computation schemes of which had been used for storm surges occurred in nearly enclosed bays, such as Tokyo, Osaka, Ise Bay, etc., and found to be very successful. In this report all the information about the storm surge will be explained, which are considered to be neccessary for future theoretical works.

1. Introduction

It is very astonishing from our experiences that such an unusually high storm surge occurred in such an open bay like Tosa Bay. Many of the severe storm surges used to occur in nearly enclosed and shallow bays along the south coast of Japan (Table 1). We have many examples of storm surges with the data of which empirical storm surge formulas are made up and numerical simulation experiments are done to clearify their dynamical features well. Speaking about Tosa Bay area, there are also many data concerning storm surges with typhoons, many of which are bigger or severer than the 7010. We can find no special differences in the parameters concerning the typhoon from those of the past except her travelling route to the landing point.

Storm surge formula for Kochi City calculated by the Kobe Marine Observatory (KOBE MARINE OBSERVATORY, 1962) with the use of weather data at the city for the typhoons shown in Fig. 1, is,

Table 1-a. Storm surges of the past (above 2.0 m)(MARINE DIVISION, J.M.A. et al. 1960, 1961, 1963, J.M.A. 1969)

Date year	month day	Station	Deviation of sea level	Bay
			m	
1959	9.26	Nagoya	3.45	Ise Bay
1934	9.21		3.1	Osaka Bay
1961	9.16	Osaka	2.6*, 2.45	Osaka Bay
1930	7.18	Benikonaya	2.5	Ariake Bay
1950	9.3	Osaka	2.4	Osaka Bay
1970	8.21	Katsurahama	2.35**	Tosa Bay
1965	9.10	Nishinomiya	2.3	Osaka Bay
1956	8.17	Benikonaya		Ariake Bay
1938	9.1		2.2	Tokyo Bay
1961	9.16	Wakayama	2.17*	Kii Channel
1917	10.1		2.1	Tokyo Bay
1964	9.25	Amagasaki	2.1	Osaka Bay
1945	9.17	Kagoshima	2.0*	Kagoshima Bay

* deduced from trances of sea water
** deduced from the neighbouring stations
*** value in Technical Report of JMA No. 28, 2.4 m in Tide Table of JMA

Table 1-b. Storm surges in Tosa Bay (above 0.8 m) (KOBE MARINE OBSERVATORY 1962, TAKAMATSU LOCAL METEOROLOGICAL OBSERVATORY 1965, KOCHI LOCAL METEOROLOGICAL OBSERVATORY 1970)

Date		Station	Deviation of sea level
1970	8.21	Katsurahama	(2.35) m
1960	8.29	Katsurahama	1.23
1964	9.25	Tosashimizu	1.08
1961	9.16	Kochi	0.91
1934	9.21	Tosashimizu	0.84
1965	9.10	Kochi	0.82

$$\Delta h = a\Delta p + b\cos\xi \cdot W^2 \qquad (1)$$

where Δh, Δp, W and ξ are estimated maximum deviation of sea level, maximum difference of pressure in mb from a standard pressure, 1010.6 mb, maximum wind speed in m/sec and its direction in degree measured clockwise from SSE observed at the weather station during the event, respectively. Fitness of the formula to the data is very well.

The calculated maximum deviation of sea level during the storm surge due to

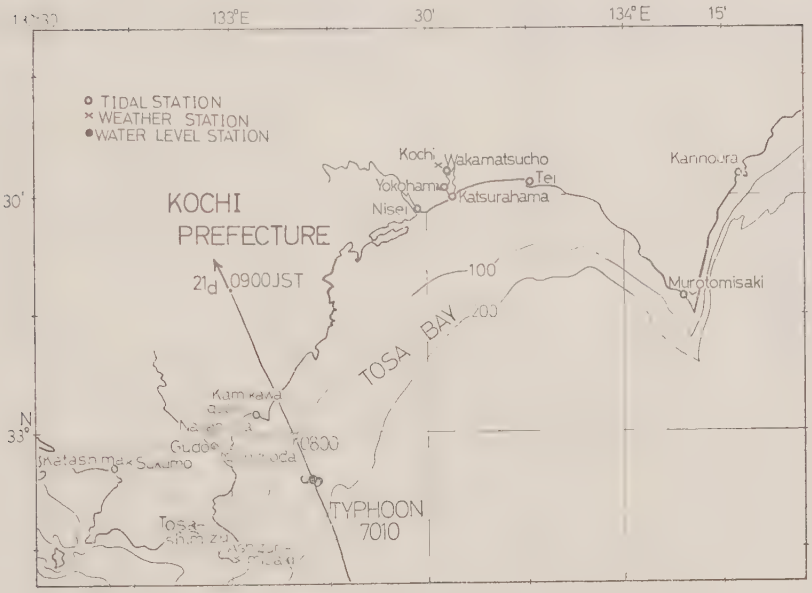


Fig. 1. Map of Kochi Prefecture.

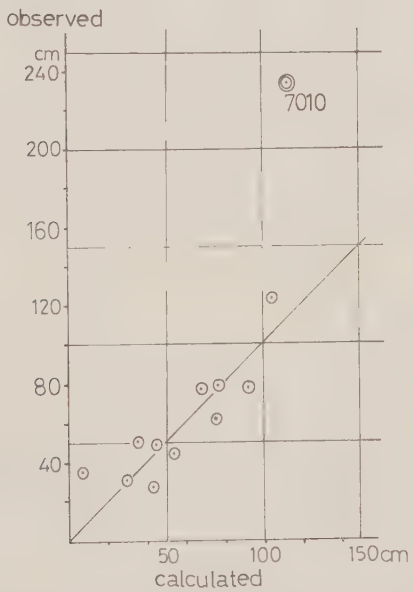


Fig. 2. Maximum deviations: observed and predicted with the formula(1) for a=2.1 and b=0.06

Table 2. Reference data for the storm surge, MA; Japan Meteorological Agency, KP; Kochi KU; Kan'noura, MM; Murotomisaki, TI; Tei, KH; Katsurahama, Kochi City, YH; Yokohama, TS; Tosashimizu, KS; Katashima, and AT; Aburatsu.

Tidal station		KM	SH	WY	KU	MM	TI
Observer		JMA	JMA	JMA	KP	JMA	KP
Tide gage		Feuse*	//	//	//	//	// **
Latitude		33°28′N	33–41	34–13	33–32	33–16	33–32
Longitude		135°46′E	′35–23	135–09	134–19	134–10	133–45
DL above TP		1.64m	3.28	1.03	1.18	2.87	
Date		′67.1	67.7	67.7		67.8	
Bench mark		4.1	9186	024–134		5142	
True height		3.297 m	1.643	3.700		10.742	
Date of mean		′69	69	69		′69	
Duration		′70–1～12	′70–1～12	′69–1～12	′70–1～12	′70–1～12	′70–5～12
Harmoni cconstants		cm °	cm °				
	Sa	14.19 171.2	13.71 167.3	9.71 109.3	15.20 163.9	14.73 174.5	
	Ssa	1.60 168.5	1.72 160.6	5.60 139.2	2.05 153.6		
	MM	2.84 202.1	3.14 199.0	0.88 197.3	3.12 196.3	4.26 172.4	
	Q1	3.55 151.8	3.68 154.3	3.81 161.9	3.43 153.7	3.67 157.4	
	O1	16.57 166.5	16.87 168.9	18.68 172.8	16.39 167.0	17.08 171.0	
	P1	7.12 184.5	7.01 188.6	7.39 190.6	6.70 185.8	7.47 191.2	
	K1	21.72 187.5	21.84 189.7	23.82 193.4	21.14 186.8	21.58 191.9	
	N1	7.78 173.3	8.12 169.1	8.24 188.3	8.15 165.4	8.03 173.7	
	M2	44.74 173.5	48.65 173.5	44.02 189.8	47.92 170.5	48.69 177.2	
	S2	20.27 195.9	21.80 199.6	21.12 211.8	21.29 195.5	21.50 201.6	
	K2	5.57 188.7	6.21 193.6	5.45 202.5	5.93 190.5	6.07 195.4	
		hm cm	hm cm				
Calcuated High		0211 46	0234 57	0242 57			
„ Low		0814 177	0848 195	0851 190			
		hm cm					
Sea level	Sea level	(0648 256)	(0820 425)	(0915 208)	0900 263	0904 509	0900 314
Observation	Instant					0908 532	
(DL) max.	Departure	1400 17	0630 24	1700 42	0900 88	0904 149	0900 121
	Monthly mean	(8) 181.0	338.2	120.8	111.7	298.9	136.9
Weather station							
Min. pressure						0647 980.2	
Max. wind						0630 E 51.7	
// instant wind						0625 E 64.3	
Precipitation, 20th						47	
// 21st						39	
Water level station							Fukabuchi
// 21 d 06 h							1.95
// 21 d max,							14.00 4.30
Wave Observation	Max, Sea					{06h E～Ⅵ 09h SE～Ⅵ	
	Max. Swell					{06h SE～Ⅵ 09h SE～Ⅵ	
Bottom inclination****						6.5	

* long-term, ** 3 days, *** daily, **** distance to the 100m depth contour in nautical mile, ♯ values at

Research Group: Abnormally high storm surge in Tosa Bay

Prefecture Office, MC; Ministry of Construction, KM; Kushimoto, SH; Shirahama, WY; Wakayama, Kochi City, WM; Wakamatsucho, Kochi City, NS; Nisei, KK; Kamikawaguchi, SD; Shimoda,

KH JMA	YH MC	WN KP	NS MC	KK MC	SD KP	TS JMA	ES KP	AT JMA
Feuse	//	Suiken	Roll	//	Eeuse	//	//***	Feuse
33–30	33–31	33–32	33–28	33–02	32–59	32–47	32–55	31–35
133–35	133–34	133–34	133–29	133–02	132–56	132–58	132–42	131–25
1.09	1.09	1.09	(2.00)		(1.34)	1.76	1.30	1.59
67–12				68.4		68.8	64.–	67.8
A 13	A 13	5003	II–1426	4639		10933	10597	9154
2.508				31.781		2.681	5.173	6.224
69						69	53	69
70–1～12	70–1～12	69–6～70–5	68–1～70–9	70–1～71–1	70–1～12	70–1～12	70–8	70–1～12
22.77 149.7	14.04 163.5	11.03 136.3	11.88 121.1	11.87 165.3	17.98 163.2	11.34 167.3		14.21 211.0
4.71 313.3	1.05 313.0	4.89 246.5	6.69 328.6	1.47 316.3	1.84 82.3	1.74 21.2		6.46 153.3
5.75 179.1	4.01 192.3	2.10 236.6	2.22 252.0	4.49 189.9	4.28 177.2	3.62 162.4		7.09 256.1
3.20 160.3	4.04 158.8	3.66 161.2	2.65 172.0	3.26 152.2	3.40 158.0	3.05 151.1		3.24 140.8
15.65 170.6	17.08 171.8	16.41 172.0	12.87 185.2	16.58 167.5	16.23 170.0	16.86 167.3		14.65 166.4
7.19 191.9	7.22 192.3	6.84 190.7	5.47 205.1	6.74 185.5	6.54 184.6	7.37 183.6		4.35 171.2
19.36 192.6	21.75 192.0	21.09 191.0	17.81 203.5	21.08 188.5	21.32 189.8	21.52 190.1		20.27 196.3
8.42 171.6	9.03 173.0	8.46 172.8	6.23 185.8	8.22 168.5	8.57 171.9	9.16 169.2		8.52 164.0
45.81 176.5	50.66 178.5	49.35 175.1	39.92 198.1	49.61 171.7	49.46 174.5	51.65 175.1		48.73 174.4
20.04 196.9	22.01 202.9	21.45 200.7	17.60 223.9	22.37 194.7	21.42 198.7	22.53 199.5		20.18 201.6
6.39 194.4	6.45 199.5	6.18 193.0	4.24 107.7	6.17 190.6	6.14 192.9	6.25 195.3		7.55 179.9
0237 60						0229 42		0241 43
0840 135						0838 192		0849 193
(0845) (422)	0910 395	0900 390	0900 480	0830 410	0850 351	0843 312	0900 255	0840 251
— (460)		0850 391		0825 (314)			0850 372	0841 329
(0850) (235)	0910 195	0910 186	0900 210	0830 144	0850 156	0900 60	0900 59	0700 22
(128.1)	131.3		223.7	(202.7)	131.1	180.1		161.4

KRM					Nakamura		Okino-shima
hm mb							
0855 979.2					0820 963.1	0729 962.3	0800 966.0
0900 E 29.2					0600NE15.7	0935SW35.8	0800 NW57.5
0905 E 54.3						0927SW46.8	
115					147	111	103#
68					40	30	31#
		Nishchi	Nakajima		Gudo		
		0.75	(0900 3.48m		1.15m		
		h m m	h m m		h m m		
		0930 2.90	1700 7.85		1800 8.18		
10h 9.1m						{06h N～Ⅸ	
(1/3 6.6m)						{09hSE～Ⅸ	
						{06h S～Ⅷ	
						{09h S～Ⅷ	
14						11	

Sukumo.

Typhoon 7010 is 113 cm, while the observed maximum is 235 cm, which are shown as ⊙ in the figure.

2. Data analysis

Data processing and analysis of the storm surge due to the typhoon 7,010 were made by the joint research team for the so-called Tosa Bay Storm Surge, menbers of which were from the MARINE DEPARTMENT* of the JAPAN METEOROLOGICAL AGENCY, METEOROLOGICAL RESEARCH INSTITUTE, KOBE MARINE OBSERVATORY** and KOCHI LOCAL METEOROLOGICAL OBSERVATORY with the sponsership of the CIVIL ENGINEERING DEPARTMENT of KOCHI PREFECTURE.

Tidal records of 15 tide stations along the coast of western Japan including the Tosa Bay area, were obtained for the period of at least one year covering Aug. 21, 1970. Tidal data at Wakamatsu-cho, Kochi City and Wakayama could not include those in August, 1970 and those at Tei and Katashima could not cover one whole year. Deviations of sea level from the undisturbed at each tide station are calculated with the use of formula,

$$\Delta h = h_{\mathrm{obs}} - (h_{\mathrm{cal}} + h_{\mathrm{cal}} - h_{\mathrm{obs}}), \qquad (2)$$

except at Tei and Katashima for which the following conventional formula is used,

$$\Delta h = h_{\mathrm{obs}} - (h_{-25} + h_{25})/2, \qquad (3)$$

where Δh is deviation of sea level, h_{obs} observed sea level of the tide station, h_{cal} calculated sea level with the harmonic constants of the station, h_{obs} observed mean sea level of the month, h_{cal} calculated mean sea level of the month, h_{-25} and h_{25} observed sea levels at 25 hours before and after the time, respectively.

Harmonic constants of tide are computed from the above-mentioned tidal data with the use of routine FORTRAN program for tidal harmonic analysis (MIYAZAKI, 1971). Along the coast of Tosa Bay and its evironments, M_2 constituent is the largest, S_2 and K_1 are nearly the same and half the amplitude of M_2, and O_1 is next to these. Propagating directions of them are NE to SW along the pacific coast of Japanese islands but in the area considered the differences of lag are within 20 to 30 minutes. Amplitude of long period constituent Sa is about 15 cm and maximum occurs in August to September and minimum in Feburary to March.

As shown in Fig. 6, typhoon 7010 was born on August 15, 1970 at 17°N and 148°E, moved to 19.5°N and 144°E, reached 27.5°N and 136°E in the morning of August 20th and from there advanced northwestwards and landed southwest coast

* H. IIDA and M. OKADA, ** M. JŌ

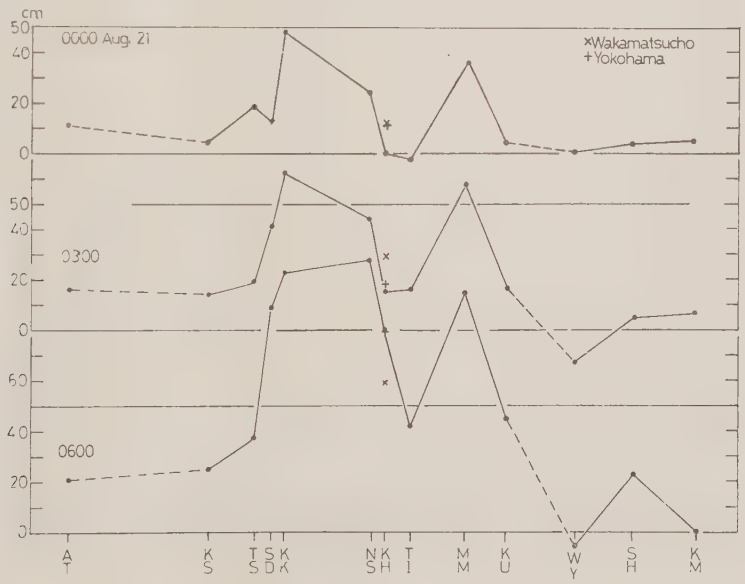
of Tosa Bay at 33°04′N and 133°07′E about 8 o'clock in the morning of August 21st, when the first high water was around Tosa Bay. The highest sea level, therefore, occurred about 0830 to 0900 JST (Table 2). Time change of the parameters cocerning typhoon 7010 is shown in table 7-a.

3. Storm surge conditions

Along the coast of Tosa Bay, deviations of sea level from the undisturbed started to rise up about 3 o'clock in the morning of August 21st. At first, the amount is higher at stations near the east and west end of the bay than at stations along the innermost part of the bay, Tei and Kochi City. From 7 o'clock when the typhoon passed the mouth of the bay, the increase of deviations became rapid and deviations reached the highest valnes between 0830 and 0900 JST. The time of occurrence of the highest values is earlier near the landing position. After deviations reached the highest, they decreased very rapidly and returned to the usual sea level about 6 o'clock in the afternoon of August 21st (Fig. 3).

At Kushimoto and Shirahama, no abnormal change of sea level due to the typhoon could be found. At Wakayama, deviation started to increase about 9 o'clock in the morning, reached the highest value, 42 cm, about 5 o'clock in the afternoon and was back to the usual sea level about 2 o'clock in the morning of the 22nd.

Fig. 3-(a)



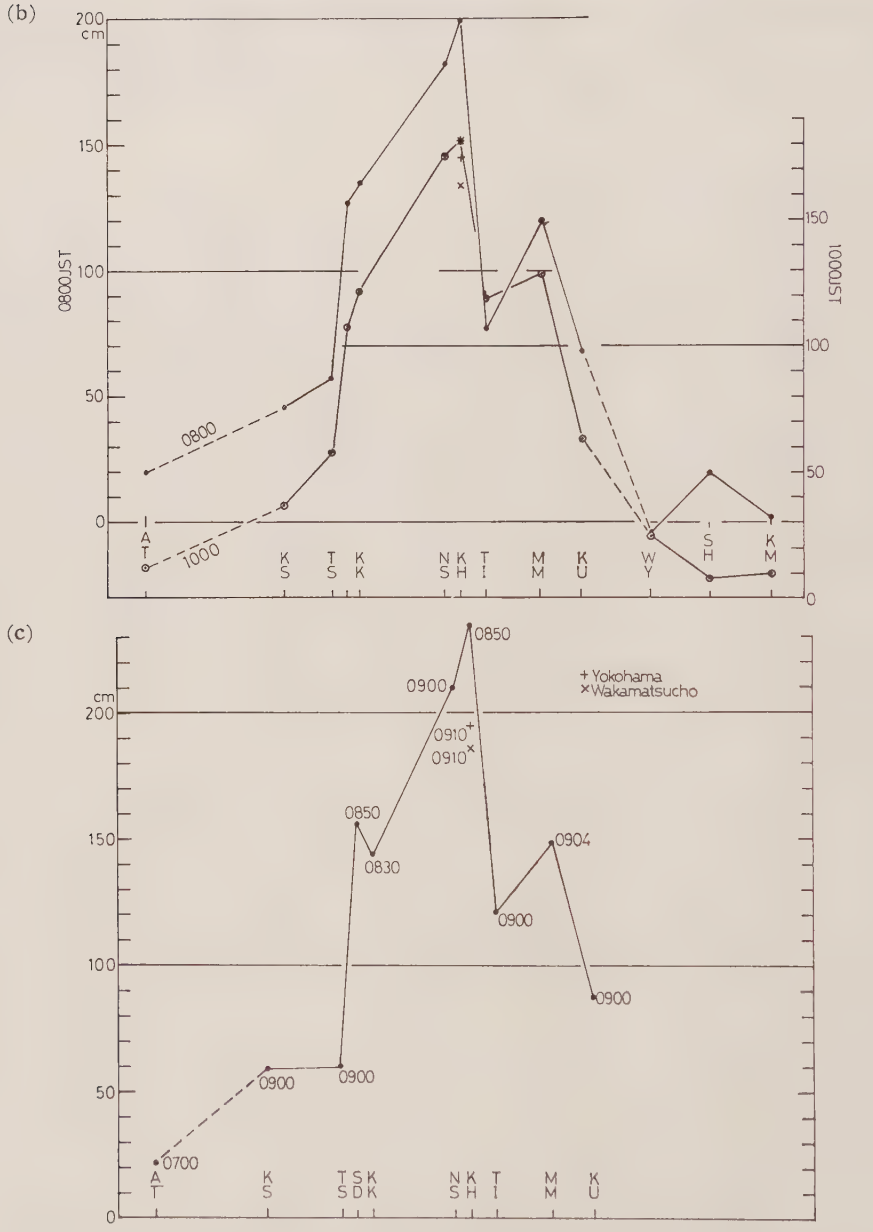


Fig. 3. Spatial distribution of deviation of sea level along the coast of the area including Tosa Bay, a, at 0000, 0300 and 0600 JST, August 21st, b, at 0800 and 1000, and c, at maximum deviation.

It is, however, not sure whether the change of sea level is due to the direct effect of the typhoon or not.

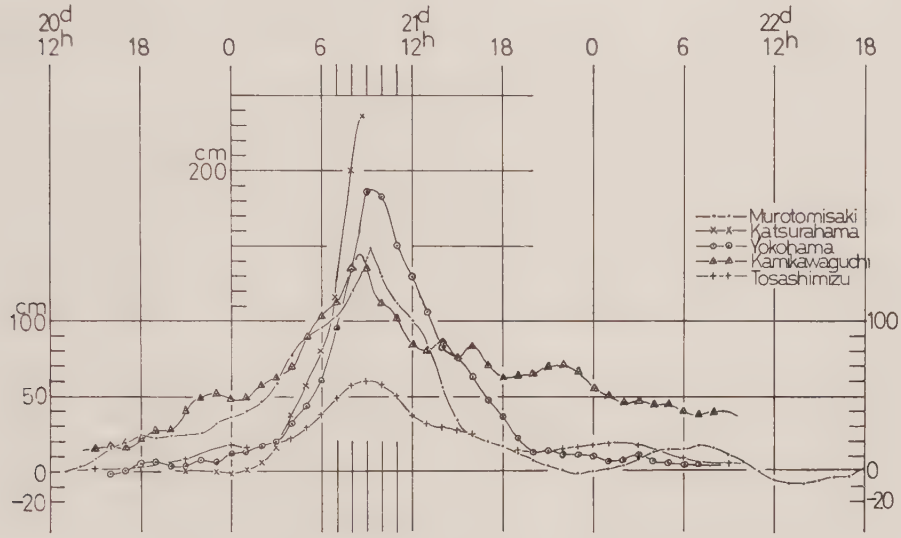


Fig. 4. Time change of deviations of sea level at representative points along the bay.

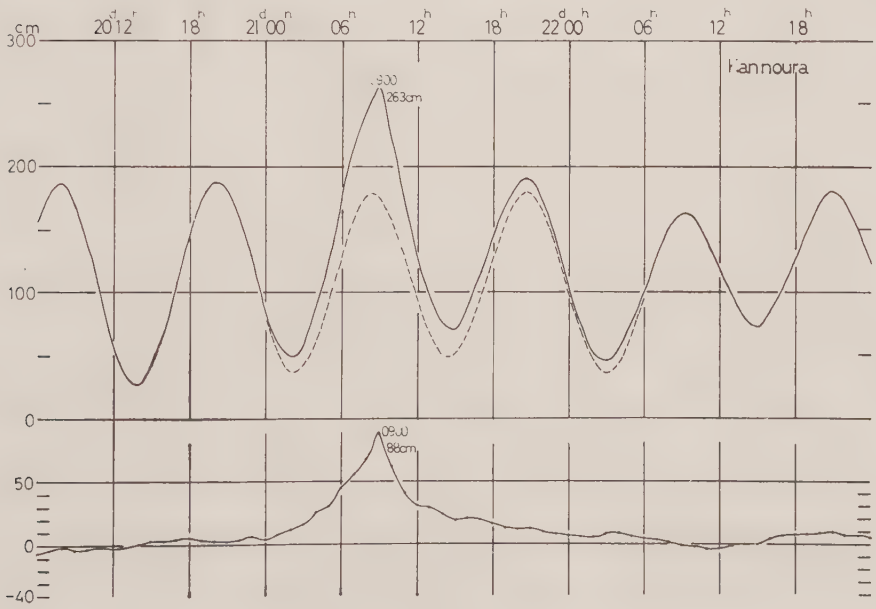


Fig. 5–a

At Kan'noura increase of the deviation started early in the morning of the 21st, reached the highest about 9 o'clock, decreased steeply to 30 cm about 12 o'clock and then gradually to the usual sea level by the 22nd (Fig. 5-a). At Murotomisaki situated at the estern end of the bay, interesting enough, devirtion of sea level started to increase much earlier than the other stations treated, that is, it showed 20 cm rise at 6 o'clock in the afternoon of the 20th, 36 cm at 0000 JST, 21st, increased to 95 cm at 6 o'clock, reached the highest value, 149 cm, at 0904 JST and then decreased rapidly to zero about 8 o'clock in the afternoon of the 21st (Fig. 5-b).

At Tei, innermost station of the bay where the calculation of the deviation was done with equation (2), a high deviation continued from 7 to 12 o'clock, a little longer than at other stations and returned to the usual sea level about 6 in the afternoon.

At Katsurahama, Kochi City, deviation of sea level started to increase from 3 o'clock in the morning of the 21st, showed rapid increase about 7 o'clock when the typhoon reached the mouth of the bay, went up to 2 m about 8 o'clock and then the tide gage was destroyed at about 0827 JST, so the highest value of the deviation could only be deduced to be 235 cm at 0850 JST from the data of the stations inside Urato inlet, Yokohama and Wakamatsucho, where the tidal records are very similar to that at Katsurahama situated at the entrance of the inlet, but tidal records show flat top near the highest sea level from 0850 to 0950 JST. It is

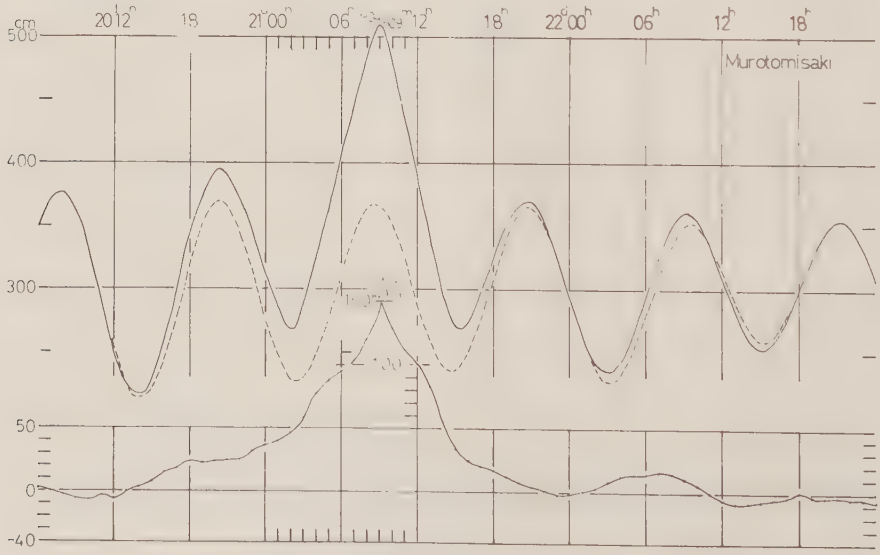


Fig. 5-b

supposed that the phenomenon is due to the lag effect of the inlet with a narrow mouth and overflow of sea water beyond its bank. Over 26,000 houses were flooded

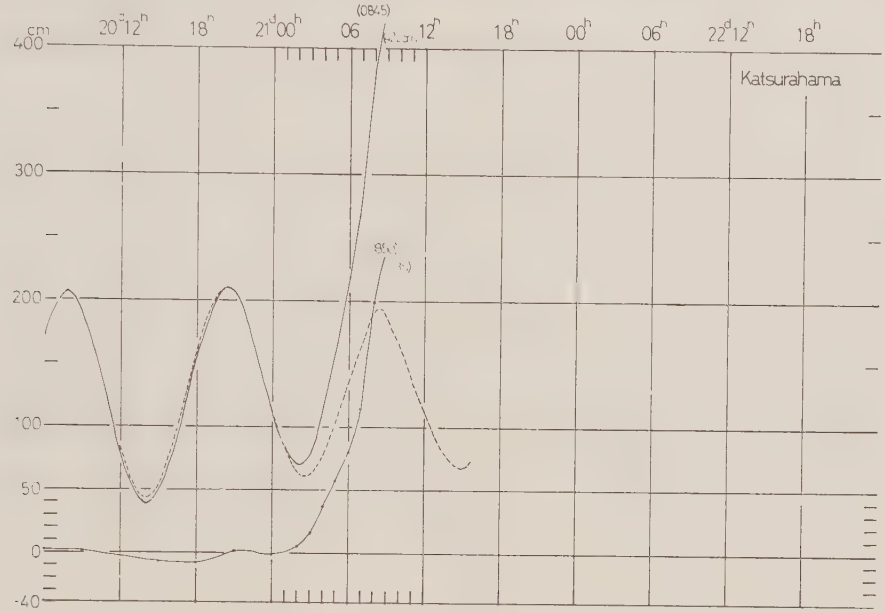


Fig. 5–c

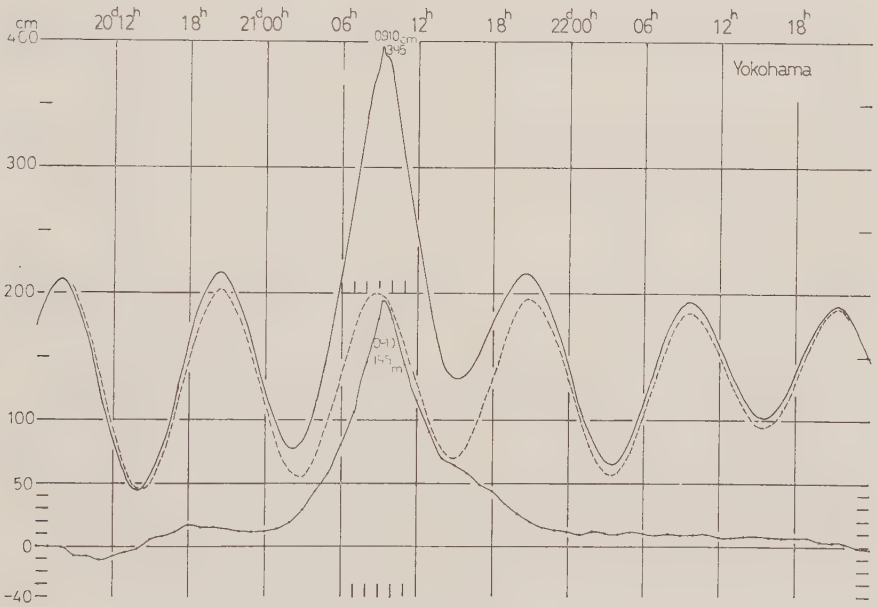


Fig. 5–d

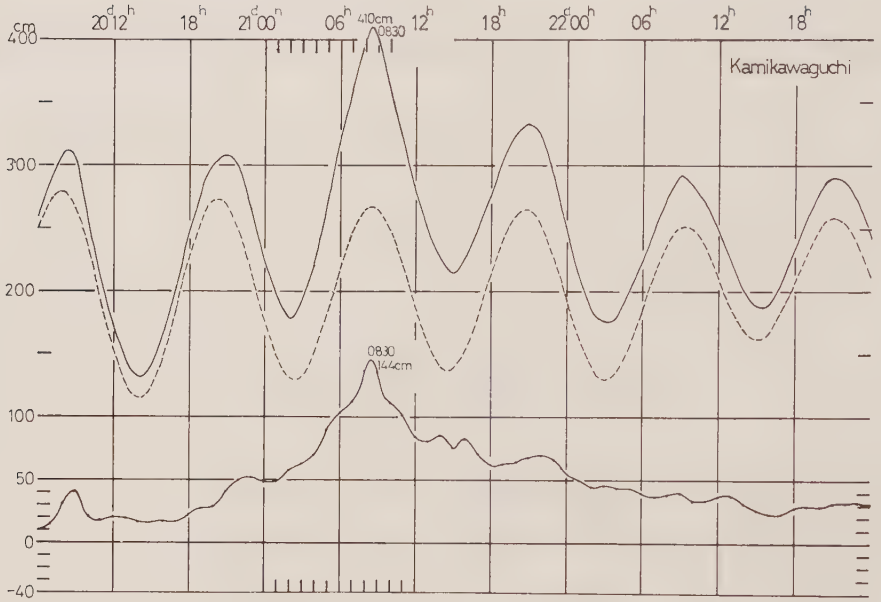

cm
400
300
200
100
50
0
-40
20d 12h
18h
21d 00h
06h
12h
18h
22d 00h
06h
12h
18h
0830
410cm
0830
144cm
Kamikawaguchi

Fig. 5–e

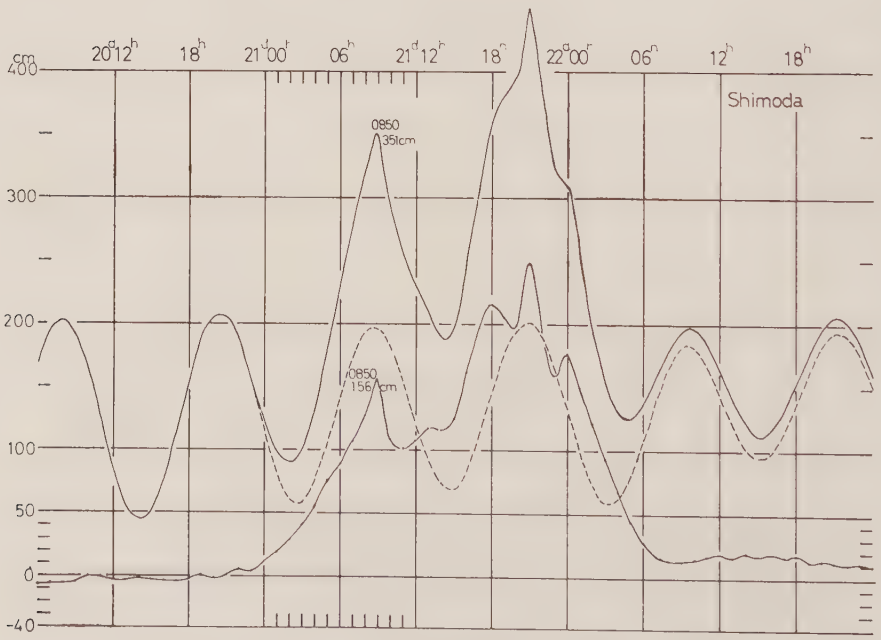

cm
400
300
200
100
50
0
-40
20d 12h
18h
21d 00h
06h
21d 12h
18h
22d 00h
06h
12h
18h
0850
351cm
0850
156cm
Shimoda

Fig. 5–f

with the overflow in Kochi City, which was the biggest disaster in the history of Kochi Prefecture. The effect of the river runoffs into the inlet was very small and faintly seen after noon (Fig. 5-c, d).

At Nisei tidal record was apt to be affected with increase of river water but the effect is supposed to become obvious after 12 o'clock from the water level record at Nakajima about 10 km up the river, so the largest deviation of sea level 220 cm is considered to be mostly due to the storm surge effect.

At Kamikawaguchi 20 km southwest of the point where the typhoon landed. The deviation of sea level had reached about 30 cm in the afternoon of 20th, and showed the highest value 124 cm at 0800 JST, earliest in the bay, and decreased rapidly to 60 cm at noon and then gradually to 0 (Fig. 5-e).

At Shimoda the largest deviation occurred at 0850 JST. The effect of the river Shimanto became obvious after 10 o'clock. At Tosa-shimizu and Katashima just outside the bay, the deviation reached maximum about 60 cm at 0900 JST. At Aburatsu the maximum deviation 22 cm due to the typhoon occurred about 0700 JST in the morning of 21st (Fig. 5-f~g).

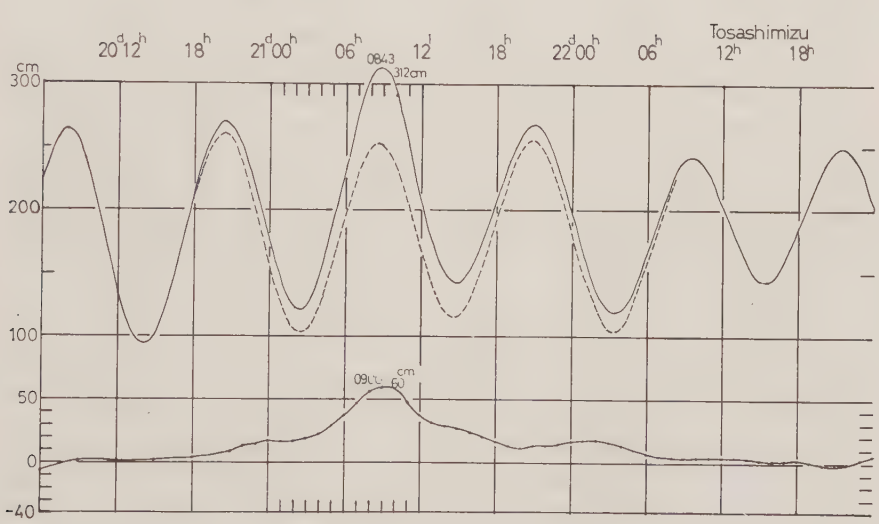


Fig. 5. Changes of observed sea level, the predicted and deviation, above figure: observed sea level in solid line and the predicted in broken line, below deviation of sea level,
a, Kan'noura, b, Murotomisaki, c, Katsurahama, d, Yokohama,
e, Kamikawaguchi, f, Shimoda and g, Tosashimizu.

Table 3. Observed sea level in cm. (above DL)

Date		KM	SH	WY	KU	MM	TI	KH	YH	WM	NS	KK	SD	TS	KS	AT
20	0	136	289	95	63	253	76	75	80	88	190	164	80	137		126
	1	119	266	55	40	230	58	51	56	64	160	140	55	112		96
	2	118	260	44	36	227	60	47	51	55	150	136	48	103		86
	3	135	280	54	53	244	78	59	63	72	155	148	60	116		97
	4	163	313	74	83	277	113	92	95	102	175	180	90	144		126
	5	198	352	106	122	335	155	133	135	142	210	220	130	185		168
	6	227	387	136	156	349	190	171	174	180	245	260	168	224		209
	7	246	412	164	180	372	214	197	201	203	277	288	195	252		241
	8	247	416	189	186	376	210	206	211	217	300	310	202	264		252
	9	230	395	186	167	360	187	188	194	205	300	304	190	252		243
	10	200	364	160	135	328	154	158	165	178	270	252	165	220		211
	11	163	324	123	96	292	116	117	123	140	240	208	125	179		167
	12	129	286	89	58	250	80	80	86	103	200	172	85	136		123
	13	108	258	54	34	225	57	52	57	63	175	144	55	106		91
	14	104	249	36	27	216	49	39	44	49	165	132	45	94		75
	15	114	263	38	42	228	67	49	56	61	168	140	50	102	48	82
	16	140	293	55	69	260	99	76	80	84	180	168	75	129	70	109
	17	176	334	85	108	300	137	113	119	123	210	204	113	169	110	150
	18	212	374	118	148	344	177	153	163	167	245	248	155	213	155	194
	19	238	402	150	175	373	204	187	195	200	280	284	190	247	193	230
	20	248	416	181	187	392	220	207	214	214	300	300	205	267	215	251
	21	241	408	190	180	390	210	207	212	213	305	308	205	266	218	254
	22	220	384	176	157	370	183	182	191	196	299	296	190	247	200	235
	23	191	347	145	124	344	147	149	159	162	275	264	155	213	165	199
21	0	158	313	110	85	312	112	112	124	132	247	224	125	176	128	157
	1	136	283	76	59	286	86	83	93	101	229	196	100	140	95	125
	2	123	266	46	49	268	75	70	77	82	213	188	90	122	73	104
	3	126	272	41	57	287	90	78	84	87	211	194	100	125	70	101
	4	146	297	56	87	324	115	114	115	118	226	220	130	147	87	118
	5	172	334	85	124	365	155	160	157	157	258	272	180	186	121	151
	6	204	372	117	174	407	200	215	215	210	320	320	230	232	160	190
	7	231	403	149	215	446	240	279	276	276	393	360	280	277	—	226
	8	246	422	183	244	484	275	382	339	340	443	400	320	306	—	247
	9	246	422	207	263	508	314	—	381	389	480	400	350	312	255	249
	10	233	402	199	220	481	290	—	369	365	442	360	290	294	231	232
	11	207	372	178	170	435	260	—	306	312	413	321	255	254	196	200
	12	179	337	147	127	390	217	—	245	255	400	279	230	208	155	163
	13	154	308	116	96	342	164	—	189	200	430	248	210	170	118	131
	14	142	294	96	75	296	135	—	146	159	475	226	190	148	102	109
	15	139	294	86	71	270	120	—	133	149	530	215	195	143	91	104
	16	154	314	102	88	273	124	—	137	149	555	228	245	154	95	117

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Date	KM	SH	WY	KU	MM	TI	KH	YH	WM	NS	KK	SD	TS	KS	AT
17	178	343	132	115	295	138	—	152	160	555	250	307	178	120	144
18	205	373	158	144	324	170	—	177	181	545	276	360	210	151	179
19	228	399	183	169	350	198	—	197	200	530	306	380	239	181	211
20	241	412	200	186	366	211	—	213	213	515	325	395	260	207	234
21	239	410	210	189	369	210	—	215	220	488	333	450	268	—	241
22	222	393	200	171	354	190	—	200	206	470	322	385	256	—	231
23	192	360	172	141	326	160	—	175	180	455	292	325	231	—	203
22 0	160	322	140	106	294	136	—	143		435	248	310	196		167
1	135	289	105	73	264	119	—	107		410	212	250	162		129
2	118	263	73	50	241	102	—	83		392	184	195	133		99
3	115	254	55	45	235	90	—	67		375	176	153	120		85
4	124	266	54	53	243	88	—	67		355	180	130	122		89
5	146	294	60	73	264	95	—	86		335	200	125	139		109
6	175	328	83	100	293	120	—	113		320	224	137	167		137
7	204	360	115	130	325	160	—	143		310	252	157	199		170
8	224	385	149	153	350	183	—	173		308	276	180	226		198
9	230	394	172	161	361	183	—	190		305	292	195	240		214
10	224	389	170	158	356	176	—	192		302	283	196	240		215
11	212	370	162	140	336	155	—	182		295	268	185	226		201
12	195	346	142	117	309	133	—	159		280	248	165	202		179
13	175	325	125	96	282	114	—	135		265	224	140	177		153
14	160	308	112	79	262	100	—	116		250	200	124	156		132
15	151	300	94	72	253	97	—	103		248	188	112	143		121
16	154	311	94	83	258	112	—	103		248	190	117	146		125
17	170	332	110	102	275	133	—	115		249	208	131	163		141
18	191	356	131	127	302	160	—	136		252	234	155	186		164
19	213	378	154	151	323	184	—	160		258	260	176	212		190
20	227	393	165	171	343	201	—	178		265	280	197	236		211
21	233	398	176	179	354	205	—	189		272	290	206	248		224
22	226	388	177	170	350	191	—	187		272	286	202	246		223
23	210	368	161	151	334	167	—	170		265	270	187	231		209
23 0	188	341	138	122	307	137	—	146		245	242	160	204		183
1	164	313	107	93	277	110	—	117		225	212	128	175		152
2	143	290	85	66	250	84	—	91		210	184	100	145		123
3	130	276	63	48	232	72	—	71		202	164	75	124		102
4	127	274	60	43	229	69	—	62		200	162	65	115		92
5	132	287	62	50	235	82	—	63		198	166	69	119		97
6	146	306	73	70	251	100	—	77		198	184	84	134		113
7	167	329	95	95	274	123	—	104		200	208	108	156		137
8	188	351	116	119	298	144	—	128		212	236	132	180		164
9	205	366	144	135	315	161	—	151		225	240	150	199		183
10	213	372	158	144	324	166	—	161		235	230	163	209		193
11	213	367	157	142	322	159	—	160		242	224	165	208		192
12	206	355	152	131	312	147	—	150		250	204	157	196		181
13	194	339	137	118	296	132	—	149		253	190	145	182		165

Table 4. Departure of sea level from the predicted in cm.

Date	KM	SH	WY	KU	MM	TI	KH	YH	WM	NS	KK	SD	TS	KS	AT
20 0	−3	−17	1	−3	−7		−23	−14		−21	3	−15	−2		0
1				−5	−7			−11		−27	2	−15			
2				−6	−4			−7		−22	3	−13			
3	−4	−6	−14	−6	−1		−19	−6		−15	1	−12	−6		−2
4				−7	−3			−1		− 8	3	−10			
5				−6	24			1		0	5	−8			
6	−7	4	−25	−6	2		2	1	−6	4	10	−7	− 7		2
7				−4	0			0	−6	10	14	−6			
8				−2	−3			0	−2	19	31	−6			
9	−4	−13	− 4	−4	−5		2	−7	0	21	41	−5	2		8
10				−3	−7			−7	4	7	21	0			
11				−2	−3			−21	4	4	17	−1			
12	−1	−17	5	−3	−6		−3	−8	3	−7	20	3	2		2
13				−1	0			−5	−2	−18	19	−4			
14				1	3			−2	3	−3	17	−1			
15	0	−7	−2	4	8		−6	6	2	3	16	−3	3		6
16				3	15			8	−2	4	17	−4			
17				4	18			12	0	9	16	−4			
18	−3	8	−14	6	24		−8	17	5	13	21	−2	4		12
19				4	21			15	6	18	27	1			
20				3	23			15	4	20	28	−1			
21	−3	−7	−3	3	24		1	14	3	20	40	1	9		14
22				4	25			12	7	24	50	6			
23				7	32			11	6	23	52	4			
21 0	6	−10	0	4	36	−3	−1	12	11	24	48	12	18	4	11
1	10	−9	−2	8	40	−3	1	14	12	31	49	19	16	0	14
2	9	−7	−11	12	40	1	6	19	16	36	57	29	17	7	16
3	6	0	−13	16	58	16	15	29	18	44	62	41	19	14	16
4	5	9	−11	26	77	29	37	44	31	56	69	55	22	21	17
5	1	18	−7	30	88	39	56	57	43	72	90	75	29	26	19
6	0	23	−6	45	95	42	80	79	59	108	103	89	37	25	21
7	1	23	−7	56	103	54	115	105	95	153	112	107	48	(31)	22
8	2	20	4	68	120	77	199	145	134	182	135	127	57	(48)	20
9	5	15	21	88	142	121	—	182	185	210	135	154	60	50	16
10	10	8	25	63	129	119	—	182	182	176	122	108	58	37	12
11	12	4	30	42	111	116	—	145	149	152	102	101	48	28	8
12	15	1	31	32	101	102	—	116	129	172	84	108	37	22	6
13	15	1	31	30	82	74	—	91	106	224	81	117	31	12	8
14	17	5	33	25	56	58	—	70	82	285	86	116	29	20	9
15	12	8	29	20	34	40	—	64	75	348	76	125	27	18	9
16	11	16	35	21	24	24	—	58	62	371	84	162	24	13	10
17	8	22	42	20	20	8	—	49	47	356	70	197	20	16	11
18	4	20	39	17	17	8	—	44	36	322	62	216	17	16	12

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Date	KM	SH	WY	KU	MM	TI	KH	YH	WM	NS	KK	SD	TS	KS	AT
19	0	16	33	13	12	9		33	22	291	63	205	13	16	8
20	−3	7	25	12	7	7		26	13	246	64	199	11	12	6
21	−6	−2	25	13	4	4		20	14	210	68	248	13	—	4
22	−8	−8	22	10	1	2		15	11	195	70	194	13	—	4
23	−11	−16	16	8	−2	0		13	10	195	66	159	15	—	1
22 0	−10	−20	15	7	−1			12	10	198	55	177	16		−1
1				6	1			9	6	198	50	150			
2				5	3			12	7	202	45	122			
3	2	−17	2	9	8			10	10	202	46	94	16		−1
4				9	12			9	6	189	44	68			
5				7	14			11	5	166	43	45			
6	4	12	−7	4	14			10	4	135	39	28	7		2
7				3	16			8	4	101	37	17			
8				2	15			10	4	76	38	14			
9	−1	6	7	−1	10			9		56	31	14	4		0
10				−2	5			9		46	34	15			
11				−4	−1			10		42	34	17			
12	4	−13	5	−4	−6			7		40	37	19	4		−4
13				−1	−9			7		40	38	17			
14				0	−9			8		39	31	20			
15	3	−9	13	0	−7			8		46	26	17	2		−1
16				5	−5			7		48	23	19			
17				7	−4			7		44	23	17			
18	−2	9	16	8	1			7		32	28	18	2		3
19				8	−3			7		19	29	13			
20				9	−3			4		8	29	14			
21	−7	−4	3	10	−3			3		5	32	12	2		−3
22				7	−4			2		3	32	11			
23				7	−4			−1		4	33	12			
23 0	0	−18	1	5	−6			−2		−1	31	10	5		−4
1				5	−7			−2		−1	31	8			
2				4	−7			−1		−5	28	7			
3	10	−5	−2	2	−6			0		15	25	3	8		2
4				1	−2			1		26	27	2			
5				−1	−2			−1		31	24	1			
6	2	14	5	0	−3			−3		27	24	−1	0		2
7				0	−3			1		16	24	−1			
8				0	−4			−1		10		−2			
9	−3	7	10	−3	−8			−1		4		−4	−9		−2
10				−3	−11			−4		0		−2			
11				−2	−13			−8		0		0			
12	2	−13	8	−3	−14			−10		8		0	−14		−11
13				−1	−16			2		17		2			

Table 5. Wave records off Katsurahama, Kochi City, measured with the wave recorder installed 260 m off the coast at the depth of 12.5 m under the mean sea level by the 3rd Regional Port and Harbour Construction Bureau.

Day	Time (JST)	Maximum Wave		Highest 1/10 Wave		Highest 1/3 Wave	
		Height	Period	Height	Period	Height	Period
		m	s	m	s	m	s
20	23.50~24.00	7.2	11.5	6.8	11.1	5.9	13.0
21	01.50~02.00	6.2	11.5	6.1	11.5	5.4	12.5
〃	03.50~04.00	7.5	7.7	6.8	11.0	6.1	12.6
〃	05.50~06.00	7.8	8.6	7.5	9.7	6.6	11.6
〃	07.50~08.00	8.8	7.6	7.6	8.6	6.5	11.0
〃	09.50~10.00	9.1	11.4	8.1	11.9	6.6	12.2
〃	11.50~12.00	6.4	13.9	6.0	12.1	5.5	12.0
〃	13.50~14.00	7.1	10.8	4.7	10.4	4.2	10.0
〃	15.50~16.00	5.4	9.8	4.7	9.2	3.9	9.1

4. Discussion

It is impossible to explain such a high deviation of sea level due to the typhoon in the empirical way of estimation and it has been unsucessful to simulate the storm surge with numerical experiments of fluid dynamic equation.

Other causes to heave up the sea level are wave set-up due to the breaking of swell and sea, rainfall on the sea, run-off of rivers, variation of the axis of the Kuroshio, etc. Wave set-up will explain some parts of the unexplained of the sea level deviation. The amount of wave set-up depends on wave height and gradient of the sea floor. It supposed to reach 60 cm in the morning of 21st at highest. Rainfall gives negligible effect on the sea level change except in almost enclosed or very shallow basin. The precipitation due to the typhoon had been 20 to 30 cm, which will made up a deviation of less than 1 cm at largest. Run-off of rivers will be very importante specially in narrow inlet or near the shallow coast, but maximum of the effect of run-off usually occurs after the peak of storm. Change of the Kuroshio or invasion of warm water mass relating to it can heave up the sea level deviation. In the following two ways, approach of the stream axis to the coast and slow down of the current speed. By this only 10 to 20cm of the deviation can be explained. In the middle of August cold water mass was found near Murotomisaki, which could not be observed any more in the middle of September.

Fig. 6. Path of the typhoon 7010.

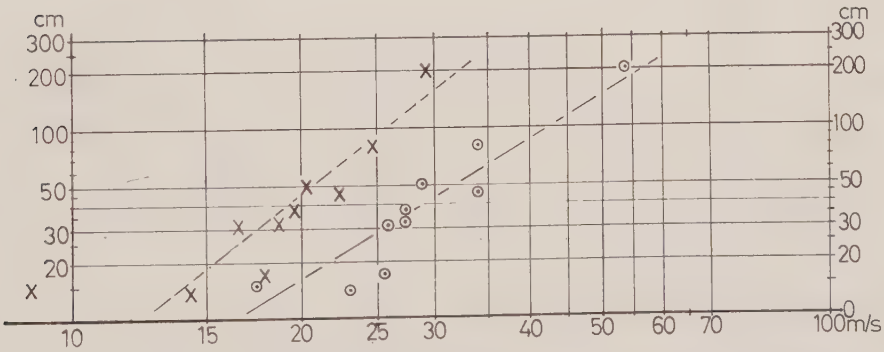

Fig. 7. Maximum easterly wind and deviation of sea level with pressure correction statically, × for maximum wind speed in 10 min. mean and ⊙ for maximum wind speed observed instantaneously.

From the comparison of data cocerning typhoons since 1934 (see fig. 6 and 7), easterly wind seems to be important, which is parallel to the coast near Katsurahama, Kochi City. In figure 7, maximum easterly wind speed and maximum deviation of sea level with pressure correction statically, are shown in logarithmic scale, from which the maximum deviation is proportional to maximum wind speed to the power of 2.5 to 3.0 and maximum wind speed observed instantaneously to the power of 2.2 to 2.5. Easterly wind, parallel to the coast, continued about 8 hours in the morning of August 21st, before and just after the landing of the typhoon.

When easterly wind starts to blow and continues, surface current is raised up westwards at first, and then becomes stronger and deviates to the coast and component of the surface drift parallel to the coast reaches maximum speed about 6 hours later, which carries near surface water to the coast and raises sea level there.

Table 6. Typhoons which gave easterly winds off Katsurahama.

Typhoon	Date			Landing Point		Minimum			Maximum		
				Lat.	Long.	Pressure	Wind		Instantaneous wind		Departure of sea level
	Year	month	day	N	E	mb		m/s		m/s	cm
6010	1960	8	29	33.4°	133.4°	969.5	E	24.9	E	34.3	123
2nd Muroto	1961	9	16	33.3°	134.2°	953.7	E	18.8	E	27.6	91
7010	1970	8	21	33.1°	133.1°	979.2	E	29.2	E	54.3	235
Kisia	1950	9	13	31.4	131.3	999.9	ESE	19.6	SE	27.5	50
Looth	1951	10	14	31.2	130.4	980.7	ESE	22.8	ESE	34.8	77
5523	1955	10	4	34.0	131.5	1007.3	ESE	16.3	ESE	26.2	37
5906	1959	8	8	33.9	135.3	975.1	ESE	18.0	ESE	26.0	55
6309	1963	8	9	32.6	131.8	995.0	ESE	20.2	ESE	29.2	76
6624	1966	9	25	34.3	133.0	999.1	ESE	8.8	SE	17.2	29
6804	1968	7	24	33.2	133.3	979.7	ESE	14.2	ESE	23.2	47

Table 7–a. Characteristic values concerning the pressure distribution due to the typhoon 7010 in Fujita's formula,

$$P = P_0 + \frac{P_\infty - P_0}{\sqrt{1+(r/r_0)^2}}$$

where P_0, P, P_∞, r and r_0 express pressures at the center, at the distance r km from the center, at the distance far from the center, the distance from the center and a parametric distance 2 times of which is the distance of maximum wind.

Time	$21^d\ 03^h$	06^h	09^h	12^h	15^h
Lat.	31.4°N	32.3	33.3	34.3	35.3
Long.	134.1°E	133.5	133.0	132.7	132.4
P_0	940 mb	955	962	973	977
P_∞	1018 mb	1016	1014	1013	1013
r_0	60 km	65	61	73	80

Table 7–b. Characteristic values concerning pressure distribution due to other typhoons (MARINE DIVISION, J.M.A. et al 1960, 1961, 1963)

Typhoon	Ise Bay	Muroto	Jane
P_0	940 mb	707.6 mmHg	968.1
P_∞	1010	749	1012
r_0	75	35	30

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土佐湾における異常に高い高潮について

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1970年8月21日高知県に上陸した台風は中規模のものではあったが，土佐湾内の特に高知市附近で大きな高潮をおこした。これを気象資料から定量的に説明する試み（数値実験その他）はすべて今までの所うまく行っていない。本報告では基礎資料をまとめ将来の調査のための一石とした。また高知市で岸に平行の東風の連吹が見られた台風による高潮は高かったことから，今回の高潮もそれがあり，東風と遠浅海岸との関連は注意すべきことと思われる。

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